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RESEARCH

Adoption and Impact of Quick Response Manufacturing Across Industry Sector

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Abstract

Quick response manufacturing (QRM) is a strategic manufacturing approach aimed at reducing production cycle times to enhance operational efficiency and competitiveness. Industries today face persistent challenges, such as delayed product deliveries, high operating costs, and inefficiencies that hinder productivity and quality. While numerous studies have highlighted the theoretical benefits of QRM, there remains a lack of consolidated evidence on its practical impact across multiple industry sectors. Specifically, there is limited comparative analysis that synthesizes QRM outcomes in diverse contexts, such as precision manufacturing, textiles, and small and medium industries (SMI). This research gap hinders a broader understanding of QRM's cross-sector applicability and its tangible contributions to production performance. To address this gap, this study evaluates the adoption and impact of QRM across various industry sectors through a comprehensive literature review, analyzing 70 academic articles and industry reports. The research focuses on three critical areas: (1) efficiency in production and delivery, (2) cost reduction, and (3) enhancement of product quality and quantity. Data was sourced from peer-reviewed academic journals, industry case studies, and relevant research reports. The findings reveal that QRM significantly improves on-time delivery by 45% and reduces production backlog by 50%. Additionally, QRM lowers warehousing and inventory costs by 35% and minimizes production downtime costs by 40%. Product quality and quantity improvements include a 30% reduction in defects and a 25% increase in output. This study fills the existing research gap by providing a sector-spanning evaluation of QRM's effectiveness and concludes that QRM is a highly effective strategy for optimizing manufacturing efficiency, enhancing supply chain operations, and reducing operational costs. It offers valuable insights for industry stakeholders seeking data-driven justifications for adopting QRM, especially in environments where responsiveness and efficiency are critical for competitiveness.

Keywords Cost reduction · Late delivery · Production efficiency · Product quality · Quick response manufacturing

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Abbreviations

ETO	Engineer-to-order
GPOLCA	Generic Paired-cell Overlapping Loops of Cards with Authorization
LM	Lean manufacturing
MCT	Manufacturing critical path time
MRP	Manufacturing resource planning
MTO	Make-to-order
OTD	On-time delivery
PDCA	Plan-do-check-act
POLCA	Paired-cell Overlapping Loops of Cards with Authorization
QCC	Quality control circle
QRM	Quick response manufacturing
TBC	Time-based competition
TPM	Total preventive maintenance
TQM	Total quality management
TP	Throughput
WIP	Work in process

1 Introduction

The global manufacturing industry is evolving rapidly due to increasing competition, dynamic consumer demands, and the advent of Industry 4.0. Companies must continuously improve operational efficiency, reduce lead times, and respond swiftly to market fluctuations. To remain competitive, businesses must adopt innovative manufacturing strategies that optimize production cycles and enhance overall agility. The requirements for efficiency and better response to client demands are becoming more urgent in the Industry 4.0 era. The fourth industrial revolution (Industry 4.0) has significantly changed companies' operational strategies. Companies face demands to quickly produce a wide range of products to meet dynamic market needs. This trend has led to challenges such as high inventory costs, low efficiency, and an increased need for flexibility [28]. The transformations in the global manufacturing landscape, such as increased competition, increasingly dynamic consumer demands, and supply chain complexity, are forcing companies to innovate their operational approaches continuously [29].

In response to these challenges, the quick response manufacturing (QRM) paradigm has emerged as a strategy focusing on reducing production and delivery cycle times. This approach helps companies improve their competitiveness with faster response times to changes in market demand [2]. QRM is specifically designed to reduce lead times in all aspects of a company's operations [68]. This approach was also first introduced by Rajan Suri in the 1980 s as a solution to improve efficiency in a low-volume, high-variety manufacturing environment [13]. QRM is an evolution of the lean manufacturing approach that focuses on reducing lead times rather than eliminating waste. Rajan Suri proposed the approach in the 1990 s, and since then, QRM has been applied in various manufacturing sectors with promising results in improving the efficiency and flexibility of operations [65]. QRM covers the improvement of production processes and extends to aspects of production planning and control, product design, and integration with supply chain partners [26].

QRM has four core principles: focus on time as the primary driver of competition, the formation of cross-functional teams, flexibility in the use of resources, and the distribution of decision-making responsibility to lower operational levels [20]. By emphasizing these principles, QRM seeks to overcome the challenges of traditional production systems, which often focus on reducing costs and increasing productivity without considering response time to consumer needs. This approach significantly improves companies' competitiveness, especially in active and uncertain markets [68].

In the manufacturing sector, QRM has significantly improved the efficiency of production processes and minimized wasted time. For example, case studies in Brazil, Europe, and the USA show that companies implementing QRM were able to drastically reduce lead times despite the challenge of changing the organizational mindset from one focused on economies of scale to one focused on time [20]. In addition, QRM can also help companies increase throughput by reducing excessive capacity utilization [26]. Not limited to the manufacturing sector, QRM is also being applied in the textile and garment industry. For example, in the Australian textile industry, the application of QRM through the integration of electronic data interchange (EDI) systems has helped to speed up the flow of information and decision-making in the supply chain. However, there are limitations in the coordination between supply chain partners [44].

However, QRM implementation is not always smooth. Studies show that a limited understanding of the core elements of QRM can be a barrier to successful implementation, especially in companies that are new to QRM. For example, companies in the USA show a higher understanding of QRM principles than those in Europe or Brazil due to better training and broader dissemination of information [25]. In addition, QRM adoption is also influenced by the specific dynamics of each industry. For example, in Russia, the concept of QRM is relatively new and less well-known. Studies show that implementing QRM in Russian industries can help overcome inventory management challenges and improve operational flexibility [28].

The implementation of QRM also brings benefits at the organizational and inter-organizational levels. For example, lead time reduction increases productivity, reduces operating costs, and improves product quality [71]. However, significant opportunities remain to advance QRM research and broaden its applications, particularly in underexplored sectors and in synergy with digital technologies introduced by Industry 4.0. A broader understanding of QRM in health care, information technology, and the service sector can unlock new potential for improving efficiency and responsiveness in highly dynamic environments. For example, studies show that integrating QRM with emerging technologies such as RFID and mobile computing systems may provide more optimized results in the future [14].

This study aims to explore the application of QRM in various industries through an in-depth literature review. By analyzing past research, this article provides insights into how QRM can be implemented to maximize operational efficiency and improve competitiveness in various industries.

1.1 Quick Response Manufacturing

QRM is a manufacturing management approach that emphasizes the reduction of cycle time (lead time) in all aspects of a company's operations [63]. The concept was developed by Rajan Suri in the late 1990 s as a more flexible strategy compared to lean manufacturing and just-in-time (JIT), especially for companies operating in a make-to-order (MTO) or engineer-to-order (ETO) environment [65, 68].

QRM focuses on reducing the manufacturing critical path time (MCT), which is the total time from when an order is received to when the product is delivered to the customer [59]. QRM aims to increase the company's flexibility and responsiveness to customer demand by optimizing production processes and reducing cycle times [52]. In the context of modern industry, QRM is increasingly relevant with the demands of rapid production and more specific orders [66], see Fig. 1). The QRM strategy uses the lean concept adapted to the progress of the century.

Figure 1 illustrates how QRM strategies can be used to improve the effectiveness of lean programs. Lean manufacturing focuses on reducing waste through process efficiency and productivity improvements, while QRM aims to reduce response time throughout the supply chain and manufacturing process [68]. These two approaches can be combined to overcome their respective weaknesses and create a production system that is more flexible and responsive to customer demand. As for the detailed information provided by Fig. 1, it is shown in the following:

1. Increased flexibility in lean with QRM: QRM allows companies to be more flexible in handling demand fluctuations by reducing lead times and increasing the adaptability of production processes [68]. Lean, which often focuses on mass production and process stability, can benefit from this approach in the face of market fluctuations.
2. Faster response time strategy: By implementing QRM, companies can reduce production cycle time and increase the speed of product delivery to customers

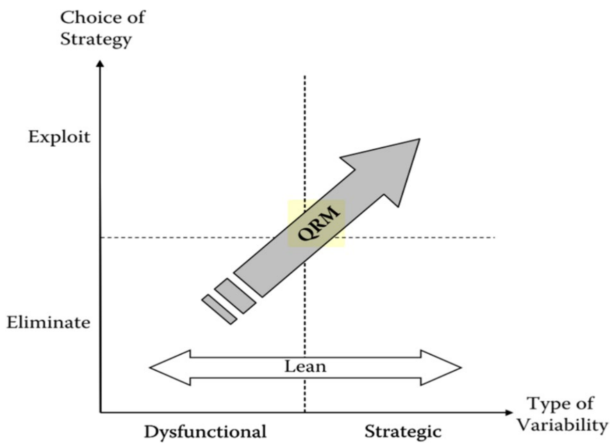

Fig. 1 Improving lean programs using QRM strategies [68]

[45, 65, 69]. This is especially important in industries that are under pressure to quickly adapt products to customer needs.
3. QRM's role in overcoming lean limitations: Lean often focuses on improving efficiency by reducing inventory and optimizing production flow. However, in manufacturing environments that are highly variable and have high demand uncertainty, this approach can lead to delays and an inability to handle sudden orders. QRM addresses these shortcomings by increasing the agility of the production system [65].
4. Impact on operational performance: Case studies show that companies using QRM strategies in lean systems experience improved overall operational performance, including improved product quality, reduced inventory, and increased customer satisfaction [65, 68].

By implementing QRM strategies in lean programs, companies can gain a greater competitive advantage in the face of rapidly changing market dynamics. As a result, this combined approach is becoming an increasingly relevant solution in the modern manufacturing industry. Table 1 shows the definitions of QRM in chronological order that are used as the basis for comparison with lean manufacturing and agile manufacturing methods in terms of similarities and differences.

Table 1 provides a chronological evolution of QRM, showing how its principles have been refined over time. This serves as a foundation for comparing QRM with lean manufacturing and agile manufacturing, particularly in terms of their similarities and differences across key aspects such as focus, production scale, strategy, and application. In terms of similarities, all three approaches emphasize improving operational efficiency, but through different means. Like lean and agile manufacturing, QRM aims to enhance workflow optimization, reduce waste, and improve production speed [51, 65]. Additionally, QRM shares agile manufacturing's focus on flexibility and responsiveness, particularly in adapting to changing customer demands and operating in high-mix, low-volume production environments [15]. Furthermore, all three methodologies emphasize company-wide transformation, involving cross-functional teams and technology integration to achieve their respective goals [24].

Despite these similarities, there are distinct differences between QRM, lean, and agile manufacturing. QRM primarily focuses on lead time reduction, whereas lean manufacturing centers on eliminating waste and achieving cost efficiency through standardization. Lean is most effective in mass production settings, while QRM is more suited to a small-batch, customized production where variability is high [20, 68]. On the other hand, agile manufacturing prioritizes rapid adaptation to market changes and demand fluctuations, making it highly relevant for industries such as automotive and electronics. Unlike agile, which focuses on market-driven flexibility, QRM adopts a time-based competitive strategy, emphasizing efficiency in shop floor operations, production scheduling, and supply chain management [15].

By analyzing Table 2, it becomes clear that QRM distinguishes itself as a time-focused strategy, setting it apart from lean manufacturing's waste-reduction approach and agile manufacturing's market-driven adaptability. This comparison

Table 1 Definitions of QRM in chronological order

Year	Author(s)	Definition of QRM
1980 s	[64]	QRM was introduced as a strategy to improve efficiency in low-volume, high-variety manufacturing environments
1998	[65]	QRM is a company-wide approach to reducing lead times, improving flexibility, and optimizing production processes
1999	[67]	QRM aims to minimize manufacturing critical-path time (MCT) to increase responsiveness to customer demands
2000	[71]	QRM reduces lead time, increases productivity, lowers costs, and improves product quality
2003	[63]	QRM is enhanced by the POLCA system, which helps manage workflow in complex manufacturing settings
2005	[18]	QRM is an operational model designed for fast response in production, with a focus on lead time reduction
2010	[68]	QRM is a time-based competitive strategy that optimizes production cycles across the entire supply chain
2012	[51]	QRM enhances flexibility and agility in manufacturing, differentiating itself from lean and agile manufacturing
2013	[24]	QRM evolved from time-based competition (TBC), focusing on reducing response time as a key competitive advantage
2014	[13]	QRM is a framework that improves job-shop production systems by increasing efficiency and reducing delays
2017	[20]	QRM's core principles include lead time reduction, cross-functional teams, resource flexibility, and decentralized decision-making
2017	[2]	QRM provides a practical approach to improving responsiveness in manufacturing by minimizing waste and production delays
2018	[59]	QRM improves on-time delivery performance by shortening lead times in engineer-to-order (ETO) production environments
2019	[56]	QRM, combined with POLCA, enhances supply chain responsiveness and minimizes waiting times
2020	[28]	QRM is an advanced alternative to traditional production paradigms, optimizing manufacturing efficiency in dynamic markets

Table 1 (continued)

Year	Author(s)	Definition of QRM
2021	[15]	QRM is effective in high-mix, low-volume, high-complexity industries, significantly reducing production delays
2021	[74]	The POLCA-integrated QRM framework enhances production performance by controlling work-in-progress (WIP) and reducing cycle times
2023	[3]	QRM minimizes inventory costs and optimizes material flow, improving overall production efficiency
2024	[1]	QRM, when integrated with lean manufacturing, enhances adaptability and responsiveness in the textile industry

Table 2 Comparison of QRM with lean manufacturing and agile manufacturing

Aspect	QRM	Lean manufacturing	Agile manufacturing
Focus	Lead time reduction	Elimination of waste	Adaptation to market changes
Scale of production	Small batch or customization	Mass production	Flexible, demand-driven
Main strategy	Time-based competition	Waste reduction	Fast response to change
Application	Complex products, variable demand	Standardized products, large volume	Specialized products, high technology

[4], [46], [68]

helps industries determine which strategy is best suited to their operational needs and market conditions.

1.1.1 QRM Key Principles

QRM is a time-based strategy that emphasizes speed and flexibility across the entire enterprise. It is designed to help manufacturers compete in a rapidly changing market by reducing lead times and enhancing responsiveness [51, 68]. The four key principles that distinguish QRM from other manufacturing methodologies are as follows:

1. Time-based strategy
   a) Time becomes a key metric in business decision-making [68].
   b) Lead time reduction is a key strategy to increase flexibility and responsiveness [51].

2. Dynamic organizational structure
   a) The use of cellular manufacturing divides the company into small, multidisciplinary teams [68].
   b) Redesigning the organizational structure to be more flexible and adaptable to changes in customer demand [18].

3. Systemic thinking pattern (system-wide enterprise application)
   a) Reduce batch sizes, setup times, and lot sizes to increase flexibility [67]
   b) Implement a systems approach that eliminates bottlenecks in production [8].

4. Enterprise application of QRM principles
   a) The focus is not only on the shop floor, but also on aspects of product design, supply chain, and administration [68].

Table 2 compares QRM with lean manufacturing and agile manufacturing based on four key aspects: focus, scale of production, main strategy, and application. Each of these manufacturing approaches has distinct objectives and methodologies suited to different industrial needs.

QRM focuses on lead time reduction and is ideal for a small batch or customized production with a time-based competition strategy, making it suitable for complex products with variable demand. Lean manufacturing emphasizes waste elimination, supports mass production, and follows a waste reduction strategy that is best for standardized, high-volume products. Agile manufacturing prioritizes adaptation to market changes, operates flexibly, is demand-driven, and relies on a fast response to change, making it ideal for specialized, high-tech products.

1.1.2 Implementation of QRM

Implementation can be accomplished in several strategic phases:

a Deployment of QRM production systems. QRM uses systems such as POLCA (Paired-cell Overlapping Loops of Cards with Authorization), which is designed to control material flow in a high-variety, low-volume production environment [19]. Case studies in the precision manufacturing industry have shown that the implementation of QRM can result in a 50% reduction in lead time and a 30% increase in productivity [59].

b QRM integration with digital technology. With the development of Industry 4.0, QRM is increasingly combined with advanced technologies such as artificial intelligence (AI), cloud computing, and big data analytics to optimize cycle time and improve demand forecasting [41].

c Application in various sectors. QRM has been adopted in various industries, ranging from automotive manufacturing to the textile industry. For example, in the precision manufacturing sector, the implementation of QRM has significantly improved production efficiency and reduced lead time [59]. In the textile industry, QRM has been applied to improve supply chain responsiveness to changes in customer demand, reduce excess stock, and improve on-time delivery [1, 44]

The application of QRM can be collaborated with several other methods to overcome the problem of waste, one of which is the ergonomic method, seen from all aspects of the work environment [48]. QRM applications in all existing supply chain activities include suppliers, office sales operations, procurement, design, engineering, and product development [34]. In 1980, Japanese companies stated that QRM was rooted in time-based competition (TBC), emphasizing time as the primary indicator. QRM can be applied to high-mix and low-volume orders to reduce waiting time [24]. The comparison between QRM and TBC resulted in a 67% impact within the analog group, 19% outside the analog category, and 14% indicating distinct differences between the two methods [17]. TBC emphasizes time as the most crucial aspect in achieving and maintaining a competitive advantage. It aims to reduce the time required to produce, sell, and ship products.

The basis of the QRM approach available from other alternative techniques for mixing push and pull systems is POLCA [34]. POLCA is a card-based visual control system that manages workflow through shop floor control in each operation to meet the delivery target [23]. POLCA prevents excessive work-in-process (WIP) when a stop comes unexpectedly [74]. POLCA integration with the decentralized application of CONWIP effectively controls WIP across the entire system, particularly in managing lengthy and varied work routes [10]. In the assembly industry, where the production of precision parts involves a series of unstable frameworks, QRM can be effectively applied, as it focuses on reducing waiting times without compromising the agility to make changes on the production floor [7, 27].

2 Methodology

The methodology in this study is designed to explore and analyze the implementation of QRM in various industrial sectors based on literature studies. This research uses a literature review method that collects, evaluates, and analyzes various scientific publications, journals, and case studies related to QRM implementation.

2.1 Research Approach

This research uses a descriptive qualitative approach by collecting secondary data from various credible academic sources to understand the successes, challenges, and strategies of QRM implementation. This approach was chosen because QRM is a complex strategy and requires a holistic understanding of its application in different industries.

2.2 Data Sources

The data sources for this study are from the following:

1. Scientific journals
    1. Journals that discuss the implementation of QRM and its impact in various industries, such as precision manufacturing, textiles, and small and medium industries (SMI) [33].
    2. Comparative studies between QRM and other manufacturing methods, such as lean manufacturing and time-based competition (TBC) [24].
    3. Scientific articles on production planning strategies and the introduction of digital systems in QRM [65].
2. Case studies
    1. Real-life cases of QRM implementation in various industries, including the precision manufacturing sector [59] and the textile industry [44].
3. Related books and publications
    1. Academic books that explain the basic concepts of QRM, such as those written by Rajan Suri, the originator of QRM [65].
    2. Practical guidance on implementing POLCA (Paired-cell Overlapping Loops of Cards with Authorization) systems and other technologies in QRM [19].
4. Industry reports and statistics
    1. Reports that measure the impact of QRM implementation on cycle time, production efficiency, and customer satisfaction [67].

2. Data from industries that have successfully implemented QRM and how it compares to other manufacturing methods [26].

2.3 Data Collection Technique

Data were collected through the following steps:

i. Identification of relevant literature

  1. Search for scholarly articles, case studies, and books that discuss QRM implementation using academic databases such as Scopus, ScienceDirect, and Google Scholar [22, 58, 73].
  2. Use keywords such as “Quick Response Manufacturing in Industry,” “QRM Implementation Challenges,” and “QRM Success Case Studies.”

ii. Source selection and evaluation

  1. Sources selected were Scopus indexed journals, Web of Science, IEEE, and manufacturing industry journals with high credibility [22, 58, 73].
  2. Case studies were selected based on successful QRM implementations and reported implementation challenges [74].

iii. Data analysis

  1. Conduct thematic analysis of various literatures to find the main trends, success patterns, and challenges of QRM implementation in different sectors [61]
  2. Comparison between companies that have successfully implemented QRM and companies that have experienced obstacles [61].

2.4 Data Analysis Technique

The analytical techniques used in this research include the following:

i. Thematic analysis.
ii. Analysis of patterns of success and challenges in QRM implementation based on case studies from different industries.
iii. Comparative analysis. Comparing the results of QRM implementation with other manufacturing methods, such as lean manufacturing and time-based competition (TBC).
iv. Meta-analysis. Integrates findings from multiple studies to identify key success indicators and barriers to QRM implementation

3 Results and Discussion

Quick response manufacturing (QRM) is a widely recognized strategy aimed at reducing lead times, enhancing production efficiency, and improving supply chain responsiveness. Despite its advantages, various challenges hinder its widespread adoption. This report identifies key research gaps in QRM across conceptual, methodological, and empirical aspects, while proposing future research directions.

A. Conceptual gaps.

Although QRM has been extensively studied, research on its integration with modern technologies, such as artificial intelligence (AI), Internet of Things (IoT), and blockchain, remains limited [28]. These technologies could improve QRM's efficiency, real-time monitoring, and decision-making. Additionally, while QRM is often compared to lean and agile manufacturing, its relationship with just-in-time (JIT) and Industry 4.0 is underexplored [24, 51]). Furthermore, QRM research has largely focused on make-to-order (MTO) and engineer-to-order (ETO) environments, with little attention given to its applicability in mass production or service industries [20]. Future research should explore AI-driven QRM models, develop hybrid frameworks that integrate QRM with lean and Industry 4.0, and assess its application in service sectors, such as health care and retail [15].

B. Methodological gaps.

QRM studies largely rely on qualitative case studies, limiting their generalizability [59]. There is also a lack of mathematical models, simulations, and optimization techniques to predict QRM outcomes in various supply chain settings [19]. Additionally, most research assesses only the short-term effects of QRM, leaving its long-term sustainability and cost-saving potential unexplored [44]. Future research should focus on AI-based simulation models to test QRM performance, conduct large-scale cross-industry empirical studies, and analyze QRM's long-term impact over 5 to 10 years [1].

C. Empirical gaps.

QRM research remains confined to specific industries and small-scale implementations, requiring broader empirical studies across different geographical regions and company sizes [2]. The POLCA (Paired-cell Overlapping Loops of Cards with Authorization) system, a key QRM tool, faces implementation challenges in complex supply chains due to capacity planning difficulties [36]. Additionally, workforce adaptation issues, such as resistance to change and training gaps, are often overlooked [61]. One of the main challenges in implementing QRM is organizational resistance. Many firms struggle to transition from cost-based efficiency models to time-based strategies, with employees and management reluctant to adopt QRM principles [2]. Companies should implement structured change management programs, including workforce training and performance-based incentives, to facilitate adoption [20]. Another challenge is the integration of QRM with existing production systems. Many companies operate on legacy systems that do not support real-time tracking and automation, making it difficult to align with QRM methodologies [28]. Researchers suggest modular QRM implementation in specific production cells before expanding to entire organizations, alongside AI-driven optimization tools for real-time decision-making [57].

Supply chain coordination issues also hinder QRM effectiveness. Many suppliers fail to meet the speed and flexibility required for QRM, leading to disruptions [80]. Strengthening supplier partnerships through long-term contracts, JIT inventory strategies, and digital supply chain management can help address this challenge [56]. Blockchain technology could further enhance supply chain visibility and coordination [42]. Additionally, high implementation costs present another barrier, especially for small and medium enterprises (SMEs). Workforce training, system upgrades, and process redesigns require substantial investments [44]. A phased implementation approach, starting with pilot projects before full-scale adoption, along with government incentives, can help mitigate these financial constraints [1, 51].

Despite its advantages, QRM research has significant gaps that limit its widespread adoption. Addressing these gaps requires further exploration of QRM's integration with emerging technologies, long-term impact studies, and large-scale empirical research. By overcoming these challenges, QRM can become a more effective and adaptable strategy for various industries.

Based on the methodology described earlier, this section discusses the study's results on the effectiveness of QRM implementation in various aspects of the industry. Table 3 below provides information on the results of implementing QRM in various industries based on the results of previous research publications.

Based on Table 3, which is the result of a representative number of QRM application publications representing related research, the discussion is divided into three main sections: (1) QRM's impact is on improving product quality and quantity and reducing unnecessary time on the production floor. (2) QRM has been shown to positively impact product quality, production quantity, and time efficiency in the manufacturing industry. (3) This section will specifically outline how the implementation of QRM can optimize these aspects with data support from various academic research.

3.1 Product Quality Improvement Through QRM

Many methods are used to maintain and improve product quality, such as applying the quality control circle (QCC), which focuses on identifying the factors that cause product defects and providing repair solutions to minimize them [47]. The application of tool redesign already uses ergonomic principles [70], and the application of the lean and plan-do-check-act (er) improves quality, efficiency, and productivity in the automotive industry. Many methods exist to enhance quality. However, the focus is always on improving and maintaining existing products. This differs from the QRM method, which focuses on minimizing waiting time and impacts all aspects. QRM involves all internal and external elements in overcoming existing problems that affect waiting times.

Table 3 Findings of QRM implementation in various industrial sectors based on previous researchers' publications

Year	Author(s)	Key idea proposed
1980 s	[64]	QRM introduced as a strategy to improve efficiency in low-volume, high-variety manufacturing environments
1998	[65]	QRM is a company-wide approach to reducing lead times, improving flexibility, and optimizing production processes
1999	[67]	QRM aims to minimize manufacturing critical-path time (MCT) to increase responsiveness to customer demands
2000	[71]	QRM reduces lead time, increases productivity, lowers costs, and improves product quality
2003	[63]	QRM is enhanced by the POLCA system, which helps manage workflow in complex manufacturing settings
2005	[18]	QRM is an operational model designed for fast response in production, with a focus on lead time reduction
2010	[68]	QRM is a time-based competitive strategy that optimizes production cycles across the entire supply chain
2012	[51]	QRM enhances flexibility and agility in manufacturing, differentiating itself from lean and agile manufacturing
2013	[24]	QRM evolved from time-based competition (TBC), focusing on reducing response time as a key competitive advantage
2014	[13]	QRM is a framework that improves job-shop production systems by increasing efficiency and reducing delays
2017	[20]	QRM's core principles include lead time reduction, cross-functional teams, resource flexibility, and decentralized decision-making
2017	[2]	QRM provides a practical approach to improving responsiveness in manufacturing by minimizing waste and production delays
2018	[59]	QRM improves on-time delivery performance by shortening lead times in engineer-to-order (ETO) production environments
2019	[56]	QRM, combined with POLCA, enhances supply chain responsiveness and minimizes waiting times
2020	[28]	QRM is an advanced alternative to traditional production paradigms, optimizing manufacturing efficiency in dynamic markets

Table 3 (continued)

Year	Author(s)	Key idea proposed
2021	[15]	QRM is effective in high-mix, low-volume, high-complexity industries, significantly reducing production delays
2021	[74]	The POLCA-integrated QRM framework enhances production performance by controlling work-in-progress (WIP) and reducing cycle times
2023	[3]	QRM minimizes inventory costs and optimizes material flow, improving overall production efficiency
2024	[1]	QRM, when integrated with lean manufacturing, enhances adaptability and responsiveness in the textile industry

QRM is combined with several other methods to overcome existing problems. QRM-incorporated POLCA can markedly increase lead time and WIP in the manufacturing industry, thus increasing profit and enabling control of the material flow that can improve performance [38, 74]). GPOLCA is a strategy used to arrange the entry and exit of production inventory to achieve better performance, and it is a QRM strategy adapted from the POLCA mechanism [19]. GPOLCA requires less WIP on the production floor than POLCA to achieve the same externality. GPOLCA requires a higher inventory with a longer response time than POLCA in achieving service levels [6]. The QRM strategy overcomes flow time and lot size optimization, such as manufacturing critical path time (MCT) [43]. In addition, combining the principles of TBC and QRM reduces lead time [24].

QRM application in producing the most extensive sheet metal products in Europe with the ETO system under high mix, low volume, and high complexity is highly effective and helps the company reduce customer waiting time [15]. QRM is also a method that can complement lean manufacturing in the scope of make-to-order, increasing industry productivity based on consumer demand [26]. The myriad consumer demands for innovative and stylish products necessitate QRM utilization in both onshore and offshore procurement models [75]. Intelligent process control and fast manufacturing cycle time are essential for the continuity achieved by adding new data to detect high-quality defects [40]. QRM can be embedded with ergonomics from work process activities to improve product quality and quantity [48]. QRM also positively impacts companies in supply chain activities because it can minimize waiting time and increase the quality and quantity of products produced by applying the POLCA system [56, 81].

The implementation of QRM significantly impacts improving product quality by reducing variability in the production process and minimizing product defect rates. A study by Tubino & Suri [71] showed that companies implementing QRM experienced improved quality control and a 30% reduction in product defects. In addition, research by Jiang & Tian [32] found that a production system responsive to market demand allows companies to adjust product specifications more quickly, thereby reducing the possibility of production defects due to changes in customer demand. Some of the key factors that lead to improved product quality through QRM are as follows:

i. Reduced lead times between production processes, which eliminate the buildup of materials that can cause product damage or contamination.
ii. Improved control at each production stage allows defect detection before processing defective products.
iii. Applying POLCA improves production flow and reduces errors due to poor planning [74].

So, the successful implementation of QRM in the industrial sector can deliver results, namely a reduced product defect rate of 30% and increased customer satisfaction due to improved quality of 25%.

3.2 Increased Quantity of Production with QRM

QRM helps companies to increase the quantity of production by reducing the time required for each production cycle. In a study conducted by Aliyev & Pykhteyeva [2], companies that an implemented QRM experienced a 25% increase in production within the first 6 months of implementation. In a study conducted by Almekki [3], companies that an implemented QRM experienced the following:

1. A 20% increase in labor efficiency due to more flexible production processes.
2. A 35% reduction in machine idle time, resulting in increased production output.

In addition, this increase in production can be attributed to several key factors:

i. Reduction in batch size, which enabled faster production and reduced machine changeover time [12].
ii. Implementation of a real-time tracking system that allows for more accurate production planning [28].

3.2.1 Reduction of Unnecessary Time on the Production Floor with QRM

One of the main benefits of QRM is the reduction of production cycle time (lead time), which has a direct impact on the operational efficiency of the company. A study by Siong et al. [59] found that companies implementing QRM were able to reduce lead time by 50%. QRM has an impact on the agility of the company in all areas in response to needs, threats, and opportunities that focus on time as a key factor [61]. Another study by Centobelli et al. [11] showed that by using fuzzy logic and QRM approaches, companies can:

i. Reduce machine changeover time by 40%.
ii. Improve on-time production by 35% due to more flexible scheduling.

The main factors that lead to the reduction of unnecessary time in production are as follows:

1. Elimination of non-value-added processes → By analyzing the entire workflow, QRM identifies processes that can be eliminated or simplified to speed production [42].

2. Use of digital technology and real-time sensors → Enables faster and more accurate production decisions [42].

3. Focus on small batches and inventory reduction → Avoids overproduction and reduces lead times in production [50].

These results demonstrate that QRM is a strategy for increasing production speed and offers far-reaching benefits in improving operational efficiency, reducing waste, and enhancing industrial competitiveness.

3.3 The Impact of the QRM on the Unexpected Costs in the Company

The implementation of QRM has significantly reduced several unexpected costs within companies, including overproduction costs, storage and inventory costs, and production failure costs. This section will outline how QRM helps companies control and reduce these costs based on various academic studies.

3.3.1 Production Cost Reduction

One of the greatest impacts of QRM is its ability to significantly reduce operating and production costs [26]. Studies by Tubino & Suri [71] show that companies that implement QRM experience a reduction in production costs of up to 20% within the first year of implementation. The POLCA model in QRM can also minimize production costs and increase productivity [57]. The main factors that led to the reduction in production costs through QRM include the following:

i. Workflow optimization, which eliminates inefficient processes and reduces waste of time and resources [2].
ii. Batch size reduction, which allows companies to save on raw material and labor costs by improving processing efficiency [18].
iii. Use of real-time tracking, which allows companies to identify and address supply chain inefficiencies more quickly [28].

In business implications, companies allocate resources more efficiently and increase profitability, avoiding overproduction that leads to waste and additional costs.

3.3.2 Reduce Storage and Inventory Costs

In traditional manufacturing systems, companies often face overstocking problems, resulting in high storage costs and the risk of expired or obsolete goods. QRM implementation has been shown to reduce storage and inventory costs by up to 35% [3]. Key factors that lead to reduced inventory costs include the following:

i. Zero inventory approach, which reduces reliance on excess inventory by producing on demand [18].
ii. Increased speed of production cycle, which allows companies to complete orders faster, eliminating the need to store large quantities of raw materials [76].
iii. Integration of ERP and AI systems, which help in automated inventory management [79].

In business implications, operational costs associated with storing unwanted goods and improve working capital efficiency have been reduced, allowing the company to allocate resources to other areas.

3.3.3 Reduced Cost of Production Failures and Waste

QRM significantly reduces the cost of production defects and waste by improving production quality and eliminating the production of defective goods. Studies by Tubino & Suri [71] show that companies that implement QRM experience a reduction in the cost of production defects of up to 40%. The main factors that lead to a reduction in the cost of production defects include the following:

i. Implementation of quality control at each stage of production, which helps to detect defects early and prevent further failed products [2].
ii. Implementation of a feedback loop system, which ensures that production processes can be corrected in real time before major defects occur [44].
iii. Reducing product lead time and handling, which helps reduce the risk of damaged products moving between production stages [79].

Manufacturing systems with rapid response to dynamic customer needs, adaptation to fluctuations in market demand, and shorter product life cycles with frequent introduction of new variants are required to meet market demands and continuously improve the system to optimize profits [72].

In business implications, warranty and product replacement costs have been reduced due to manufacturing defects, and customer confidence is increased due to higher quality products.

3.4 Effectiveness of Quick Response Manufacturing (QRM) in Overcoming Product Delivery Delays to Consumers.

QRM has proven to be a highly effective strategy for reducing product delivery delays, improving production efficiency, and adapting production processes to market needs. This section outlines how the implementation of QRM can address the challenges of product delivery delays, supported by data and academic studies.

3.4.1 Improved Product Delivery Timeliness

A study conducted by Siong et al. [59] showed that companies that implemented QRM experienced a 45% improvement in on-time delivery. This can be attributed to a few key factors:

1. Reduction in manufacturing lead time: QRM directly reduces the manufacturing critical path time (MCT), allowing customer orders to be processed faster and shipped on time [43].

2. Elimination of production bottlenecks: The implementation of the POLCA system in QRM optimizes the production flow and reduces potential delays in manufacturing [74].

In business implications, companies can now improve their competitiveness by meeting delivery promises on time and reducing the cost of delays that can result in fines or compensation to customers.

3.4.2 Reduce Backlogs and Production Delays

One of the main causes of delivery delays is the accumulation of orders (backlog) that impedes the flow of production. A study by Rog [54] found that implementing QRM can reduce production backlogs by 50%. The main factors of backlog reduction in QRM are as follows:

i. The use of a production cell-based work system (quick response cells/QRCs), which speeds up decision-making and production processes [67].
ii. More flexible capacity management, which ensures the availability of production resources when new orders are received [2].

In business implications, customer dissatisfaction is reduced due to delivery delays, and operational efficiency is improved by avoiding excessive order backlogs.

3.4.3 Production Flexibility in Response to Changes in Market Demand

In dynamic industries, delays often occur due to sudden changes in customer demand. Studies by Gromova [28] show that companies using QRM-based systems are able to adjust production to customer demand 35% faster than conventional production systems. Key factors for increased production flexibility are as follows:

i. Adoption of digital systems and real-time data analytics that allow companies to organize production schedules based on customer demand patterns [35].
ii. Reduced production setup time, which allows companies to quickly switch to the production of different items without losing time, is beneficial [77].

In business implications, the company's ability to adapt to market trends without experiencing production delays is improved and ensures that products delivered to customers always meet their needs and expectations.

3.4.4 Improved Supply Chain Efficiency

The implementation of QRM not only affects internal production, but also supply chain efficiency, which is an important factor in the timeliness of product delivery to consumers. The POLCA system, combined in a hybrid system in the management of material flow on the production floor, also has the best impact in improving all the performances based on the evaluation results of WIP, throughput (TP), MCT per job, and on-time delivery (OTD) [37]. POLCA can organize and limit the number of jobs running on the production floor to achieve shorter turnaround times [49, 53]. Thus, the application of POLCA can overcome the problem of parts shortage in the manufacturing process to reduce waiting time and have an impact on product delivery that is correct or in accordance with the agreed time [36]. According to a study by D. Yang & Zhang [80], companies that implement QRM in their supply chain experience the following:

i. Reduced reliance on excess inventory, which reduces the risk of delays due to unavailable inventory.
ii. Increased supply chain visibility, which allows for better communication between suppliers, manufacturers, and customers.

In addition, research by Cachon & Swinney [9] shows that QRM strategies increase the speed of product distribution by 40%, allowing companies to replenish inventory at various distribution points more quickly.

In business implications, delivery efficiency is improved so that products can be delivered on time without having to store excess inventory and reduce logistics costs through more efficient planning.

3.5 Analysis of Successful Implementation of Quick Response Manufacturing (QRM) in Industry

Figure 2 shows the pie chart of QRM implementation in the industrial sector, which has been generated. We can analyze the success of QRM implementation in the industry from three main aspects: production and delivery efficiency, reduced operating costs, and improved product quality and quantity.

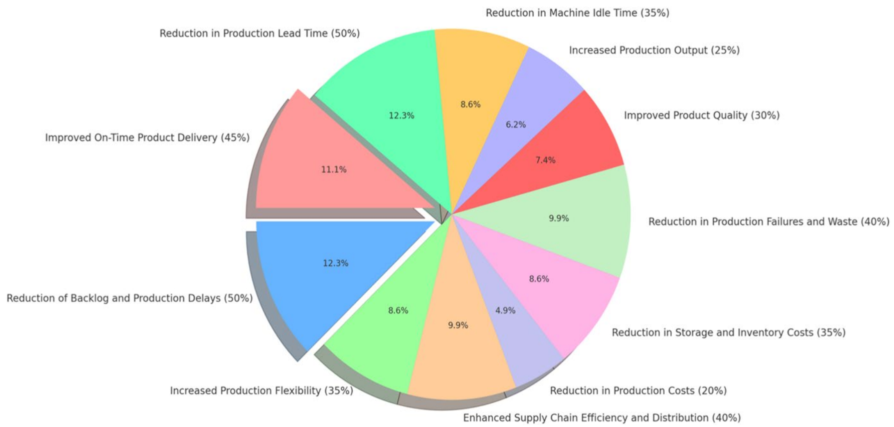

Fig. 2 Percentage of successful QRM implementation in industry

3.5.1 Product Manufacturing and Delivery Efficiency

This category includes factors related to reducing delays in production and delivery of products to customers and increasing flexibility in the supply chain:

i. Production lead time reduction (50%).

   QRM has been able to reduce production lead time by 50%, which means that the cycle time from the start of production to the product being ready for shipment has been cut in half. This directly improves the efficiency of the supply chain and minimizes delays [59].

ii. Reduction in backlogs and production delays (50%).

   The implementation of a work system based on quick response cells (QRCs) and POLCA technology helped to avoid order backlogs that caused production delays [54].

iii. Improved product delivery timeliness (45%). QRM improves the speed and accuracy of product delivery, allowing companies to better fulfill customer orders [74].
iv. Improved supply chain and distribution efficiency (40%).

   By reducing reliance on excess inventory and improving supply chain communication, QRM makes the distribution system faster and more efficient (D. [80]).

3.5.2 Operational Cost Reduction

This category focuses on the effectiveness of QRM in reducing unexpected costs, including overproduction, inventory, and production defects:

a Production cost reduction (20%). By optimizing manufacturing processes and reducing non-value-added activities, companies can reduce production costs by 20% [71].
b Reduce warehousing and inventory costs (35%). Companies that implement just-in-time inventory and zero-inventory approaches experience a 35% reduction in inventory costs [3].
c Reducing production defects and waste costs (40%). Implementing a QRM-based quality control system helps reduce production costs due to defective products by 40% [44].

3.5.3 Improved Production Quality and Quantity

This category focuses on QRM's ability to increase production output and product quality, thereby increasing customer satisfaction:

a Improved product quality (30%). QRM implementation improves product quality through strict control at each stage of production, reducing manufacturing defects by 30% [50].
b Increased production volume (25%). Reduced idle time and improved labor efficiency resulted in a 25% increase in production quantity [2].
c Reduced machine idle time (35%). With the implementation of a real-time tracking system and batch size optimization, QRM reduced machine idle time by 35% and increased labor productivity [42].

3.5.4 Challenges in Implementing Quick Response Manufacturing (QRM)

While QRM has been shown to provide several benefits in improving production efficiency, reducing costs, and accelerating product delivery to customers, several challenges must be considered when implementing QRM. The following are key challenges in implementing QRM, along with references from various academic studies.

i. Lack of understanding and awareness of QRM principles

One of the biggest challenges in implementing QRM is the lack of understanding of QRM concepts and principles, especially in companies that are still oriented towards traditional approaches, such as lean manufacturing [25, 31]. This study found that many companies have only partially adopted elements of QRM without understanding how to optimize it thoroughly [60].

Solution: Companies must provide intensive training and technical assistance to their management team and workforce to implement QRM effectively [5, 68]. Furthermore, case studies from companies that have successfully implemented QRM should be used as benchmarks to increase awareness and provide practical insights [68].

ii. Organizational resistance to change.

Implementing QRM requires fundamental changes in the work culture and mindset of the organization. One of the main barriers organizations face is resistance from management and employees to changes in the production system [2]. Resistance may stem from uncertainty, fear of job loss, or discomfort with new processes [61]

Solution: Build a more flexible organizational culture by involving employees in decision-making and demonstrating the long-term benefits of QRM [15]. Leadership engagement and effective communication play a key role in mitigating resistance. The ADKAR change management model [30] can be used as a structured approach to facilitate change.

iii. High implementation costs.

QRM implementation often requires a significant initial investment, including the cost of training employees and implementing new management systems [59]. Many organizations, especially small and medium enterprises, experience constraints in allocating financial resources for QRM implementation.

Solution: Companies can start with a small pilot project before fully implementing QRM. Implementing QRM incrementally in high-impact areas can also help optimize budget allocation [3]. Additionally, organizations can explore government grants and industry partnerships to support the transition.

iv. Technology constraints and digitalization.

Optimal QRM implementation requires the support of digital technologies, such as enterprise resource planning (ERP) and AI-driven analytics, to increase the speed of decision-making [28]. However, many organizations still have limited technology infrastructure.

Solution: Integrate digital systems in stages, starting with the implementation of real-time tracking and simple data analytics to improve production efficiency. Adopting cloud-based solutions can also enhance accessibility and scalability [78]. Companies should also prioritize cybersecurity to protect digital assets [38].

v. Supply chain coordination difficulties.

QRM emphasizes speed in order fulfillment, but its success is also highly dependent on the timeliness of raw materials from suppliers. A lack of coordination in the supply chain can cause delays, contrary to the principles of QRM [16, 80].

Solution: Establishing stronger supplier relationships through collaborative planning and digital supply chain management tools can improve coordination [39]. Implementing vendor-managed inventory (VMI) can further enhance supply chain synchronization [62].

vi. Difficulties in implementing the POLCA system.

The POLCA system is a key method in QRM to manage production flow and avoid backlogs. However, many companies experience difficulties effectively implementing POLCA due to errors in production capacity planning [74].

Solution: Companies need to conduct regular production capacity analysis so that the POLCA system can operate optimally. Simulation models can also aid in fine-tuning POLCA for different production environments [43]. Additionally, training production teams on POLCA best practices can enhance its effectiveness [68].

vii. Mass production incompatibilities.

QRM is designed for low-volume, high-variation production. As a result, some mass production companies have difficulty implementing this concept [52].

Solution: Companies implementing mass production can adapt some elements of QRM, such as increased flexibility in production management [55]. Hybrid approaches that integrate QRM principles with lean manufacturing can also enhance efficiency [26].

viii. Complexities of implementation on a global scale.

Companies with international operations face additional challenges in synchronizing production and logistics across locations. Implementing QRM in global supply chains is more complex due to differences in regulations, business culture, and technological infrastructure in each country [21, 55].

Solution: Develop a flexible QRM strategy that can be adapted to the specific conditions of each production site [81].

Although QRM offers several advantages in manufacturing efficiency and lead time reduction, some significant challenges in its implementation include a lack of understanding of QRM principles, resistance to change, high implementation costs, technology limitations, and challenges in supply chain coordination and POLCA system implementation. However, with the right strategy, companies can overcome these challenges and optimize the benefits of QRM to improve their competitiveness.

3.5.5 Analysis of the lack of success in the implementation of QRM

Despite its potential, the implementation of QRM faces significant challenges that can undermine its effectiveness. One of the primary issues is a lack of understanding and awareness, leading to partial or incorrect implementation. Many companies misinterpret QRM as a minor extension of lean manufacturing rather than a fundamental shift towards time-based competition. While training programs and workshops [25] can improve understanding, they are insufficient unless accompanied by management commitment and operational restructuring. Another major challenge is resistance to change, particularly from employees and management who are accustomed to cost-based efficiency models. QRM requires organizations to prioritize lead time reduction over cost minimization, which often conflicts with traditional financial metrics. While change management strategies and employee engagement [2] can help, deeper structural changes, such as realigning performance metrics and incentives, are necessary to fully embed QRM principles.

Operational challenges also pose significant risks. The POLCA system, a core component of QRM, struggles with poor capacity planning, making it inefficient in complex, high-variability supply chains. Solutions such as customized POLCA frameworks and AI-driven decision-making [36, 74] have been proposed; yet, empirical validation remains limited. Without further research, POLCA may remain a theoretical concept rather than a scalable industry solution. High implementation costs further hinder QRM adoption, particularly for SMEs that lack the financial resources to invest in training, restructuring, and system upgrades. While government incentives and gradual implementation [44] can ease financial strain, many SMEs lack the operational flexibility to sustain prolonged transitions. Without scalable, low-cost frameworks, QRM risks becoming a methodology reserved for larger corporations.

Technological barriers also pose significant limitations. Many firms still rely on legacy systems that lack real-time tracking, AI, and automation, making QRM integration difficult. A modular digitalization approach [28] has been suggested, but partial implementation can lead to fragmented and ineffective systems. A full digital transformation strategy is required to ensure seamless real-time data flow across the supply chain. Another fundamental issue is QRM's incompatibility with mass production. Designed for low-volume, high-mix environments, QRM does not align well with high-volume batch production models. Although hybrid QRM-lean models [1] have been suggested, these remain largely theoretical, with limited empirical validation. This raises concerns about QRM's universal applicability beyond niche industries.

Supply chain coordination issues further complicate QRM implementation. Many suppliers struggle to match QRM's demand for speed and flexibility, leading to bottlenecks. Strengthening supplier partnerships through long-term contracts and digital supply chain management [80] is one approach, but not all suppliers have the infrastructure or financial capacity to comply, potentially increasing supplier dependency. Finally, a lack of long-term performance studies makes it difficult to assess QRM's sustainability and competitive advantage. Most research focuses on short-term efficiency gains, leaving QRM's long-term benefits uncertain. Calls for longitudinal studies over 5–10 years [1] are necessary to validate its effectiveness, but until then, claims of QRM's superiority remain speculative.

4 Conclusion

Future research on QRM should focus on several key areas to enhance its applicability and effectiveness. Firstly, integrating modern technologies such as artificial intelligence (AI), the Internet of Things (IoT), and real-time tracking could significantly improve QRM's efficiency and decision-making processes [28]. Additionally, the development of hybrid manufacturing models that combine QRM with lean and Industry 4.0 principles would provide a more adaptable and scalable approach for various industries [25]. Another critical area of study is the need for longitudinal research, where long-term case studies spanning 5 to 10 years could assess the sustained operational and financial impacts of QRM implementation [1]. Furthermore, expanding comparative research across different sectors such as health care, automotive, and retail would help determine the effectiveness of QRM beyond its traditional manufacturing applications [15]. Finally, optimizing supply chain management through digital tools, blockchain technology, and predictive analytics could enhance supplier coordination and reduce delays in QRM adoption [80]. By addressing these research directions, QRM can evolve into a more robust and adaptable strategy capable of driving efficiency improvements across diverse industries.

QRM has proven to be a versatile strategy applicable across multiple industry sectors. Implementing QRM has proven effective in improving production efficiency, reducing operating costs, and accelerating product delivery to consumers. This study shows that QRM can reduce lead time by 50%, improve on-time delivery by 45%, and reduce production backlog by 50%, significantly reducing production delays. QRM helped the company reduce inventory costs by 35% and production downtime costs by 40%, making it an effective strategy for reducing unnecessary expenses. In addition, product quality and quantity improved, with a 30% reduction in manufacturing defects and a 25% increase in production output. As a result, QRM is a production acceleration method and a holistic approach that optimizes the entire manufacturing value chain. Therefore, companies that want to improve their competitiveness and operational efficiency are strongly advised to implement a QRM system to face the increasingly competitive market dynamics.

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Competing interests The authors declare no competing interests.

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