Operations Strategies for Sustainable Manufacturing: Insights from a Chinese Medical Device Case Study

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Abstract— **This paper examines multi-stage scheduling for sustainable manufacturing, drawing upon a real case study of a Chinese medical device manufacturer, in order to explore operations strategies for sustainable manufacturing. It considers the balance between demand, capacity resources, and social responsibility. Optimization models applied in a production system are affected by objectives and constraints that reflect business processes and rules. The business model structure has a significant influence on production planning and control problems.The literature indicates that the lack of sustainability considerations complicates rapid responses to changes. The topic of this study is to propose a business model that incorporates a closed-loop knowledge-sharing loop to address these challenges. The model is applied to a real Chinese medical goods company to demonstrate its effectiveness.**

I. INTRODUCTION

Since the last century, mass production has been utilized to meet the demands of world markets in terms of volume and variety. In today's increasingly competitive global market, new policies are being implemented, such as lean production to reduce costs and waste, and mass customization to satisfy varied demands and services with expected quality. Sustainability is the main challenge facing the manufacturing industry in the 21st century, and it also has its own policies. Industry 4.0 was created to enable intelligent and sustainable production. According to [16], Industry 4.0 strategies should consider environmental and social factors in addition to profit maximization. To evaluate a company's sustainability performance, various methods have been proposed, including product lifecycle analysis [1], sustainability performance assessment [5] and corporate social responsibility [4].

However, these methods can be challenging to implement due to their broad scope, data requirements, and reliance on multiple indicators. In the pursuit of enhanced sustainability, corporate entities may find it advantageous to direct their attention towards the operational aspect, which is significantly influenced by functions that extend beyond the manufacturing process. Consequently, a comprehensive understanding of business models and the strategic exploitation of their characteristics can lead to a substantial enhancement in manufacturing performance.

The present study explores the impact of Sustainable Business Models (SustBMs) on production planning and control in manufacturing. The objective of this article is to identify how to articulate processes using Sustainable Business Model (SustBM) that can contribute to improving corporate sustainability. Insights from a case study of a Chinese medical device manufacturer are presented.

The structure of the paper is as follows. Section 2 discusses the concept of the business model, which begins with a literature review and then explore the sustainable potential of the existing model. This paper describes a use case in which a Chinese medical device manufacturing company aims to enhance its existing business process models and evaluate its sustainability performance using Key Performance Indicators (KPIs). Section 3 proposes a close-loop knowledge business model for sustainable management systems based on selected sustainability indicators. The proposed business model and process for this case company enables it to respond quickly to changes in demand and shortages of materials and machinery. Section 4 discusses the methodology for selecting KPIs when implementing SustBM, while Section 5 covers applying the DMAIC method and sustainability indicators to a real case. Section 6 summarises the main results and indicates the future direction of this study.

II. SUSTAINABLE BUSINESS MODELS

The concept of Sustainable Business Model (SustBM) considers social factors, besides economic and environmental dimensions. The definition of SustBM, proposed by many scholars ([19], [9]), is as follows: SustBM is an orchestration of the processes to create, deliver, capture, and exchange value considering the three dimensions of sustainability. The Business Model Innovation concept refers to the conceptualization of a new business model and the transformation from a current business model to a new one [8]. This conceptualization proposes two possible ways to achieve SustBM:

- by adding environmental elements (such as footprint emissions) to an existed circular material flow model ([13], [14]);
- by integrating the concepts of circular economy, sustainability, product-service system into a conventional linear process model [11].

The purpose of this section is to compare various proposed SustBMs based on their contribution to business in terms of sustainability dimensions and planning horizons.

- **Economic dimension (profitability):** Model 2 from the Table 3 adopts sustainability principles from the strategic level to promote well-received, green designs to capture profits. The update of Bill of Materials

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Model	Author	Sustainability dimensions			Planning horizons		
		Economic	Environment	Social	Strategy	Tactical	Operational
1	(MacArthur, 2013) [13]		x	x	x		
2	(Lacy et al., 2016) [11]	x	x	x	x	x	
3	(Lozano, 2018) [12]	x	x	x	x	x	
4	(Geissdoerfer et al., 2018) [8]	x	x	x	x		
5	(Goni et al., 2021) [10]	x	x	x	x	x	x
6	(Wang et al., 2022) [18]	x	x	x	x	x	x
7	(Salwin et al., 2024) [17]	x	x	x	x	x	x

TABLE I

COMPARISON OF SUSTAINABLE BUSINESS MODELS (SUSTBMS)

(BOMs) and manufacturing processes under demand changes and supply shortages can be largely mitigated through modular design and cell production ([7], [3]), instead of excessive inventory of material and product [2]. Less attention has been paid to the operational level. Models 3 and 4 emphasize integrating sustainability into a company's core strategy by involving both internal (employees) and external (customers, society) stakeholders to increase market share and customer loyalty.

However, implementing such strategic changes can require significant up-front investment and may not deliver immediate bottom-line benefits. Instead, the focus is on building a resilient and adaptable business that benefits from sustainable practices over the long term. In addition to considering green designs, Model 5 includes decisions that support sustainable development from the operational level by actively guiding customers toward more sustainable product choices. its strengths lie in its actionable strategies for guiding customer behavior. In addition to customer demand, the proposed model takes cost factors into account. By strengthening communication with customers, it facilitates timely adjustments to alternative demand and delivery schedules, helping to reduce penalty costs. This is particularly beneficial during periods of high demand when raw material shortages and capacity constraints may occur.

- **Environmental dimension (Resource Use efficiency):** All three models show that material availability is impacted by the forward and backward flow of materials. An integration of actors from the whole supply chain contributes to material use efficiency. Model 1 also emphases on energy emissions from transformation and transportation in the whole life-cycle of a product. The proposed model considers energy consumed from production to make decisions of accepting demands, as well as energy consumed from purchasing to make decisions of material replenishment and time of responsiveness. Model 2 pays little attention to Energy consumption. Model 3 encourages companies to adopt eco-design principles that consider the entire life-cycle of a product, from material sourcing to disposal. By doing so, companies can design products that use fewer resources, are easier to recycle or reuse, and have a longer lifespan, thus improving overall resource efficiency.The model also emphasizes the role of stakeholders (employees, suppliers, customers, etc.) by engaging stakeholders in sustainable practices, businesses can innovate in resource-saving technologies, materials, and processes that optimize resource use across the entire supply chain. Model 5, however, focuses on optimizing the use of materials and resources at each stage of the product life-cycle. The proposed model is highly process-oriented and offers direct solutions for reducing the consumption of raw materials and minimizing resource wastage through closed-loop systems.
- **Social dimension (Influence on employee, customer and society):** All three models consider the impact of business activities and behavior on society as a whole by reducing consumption and waste. Model 2 and the proposed model also consider increasing customer satisfaction by improving product design and service. Model 3 focuses on employee engagement by fostering a sense of purpose and professional growth through skills development, Model 3 also considers building stronger relationships with customers by educating them about responsible consumption and increasing trust through ethical business practices. Model 3 can benefit communities by promoting business practices that reduce inequality. Model 4 emphasizes the importance of strengthening community engagement to promote economic growth. It also highlights the need to increase employee training to improve their skills and job satisfaction, while focusing on improving the overall work environment. Model 5 also mentions encouraging employees to participate in corporate sustainability projects.

  However, the operational focus on equity is more detailed than in the previous models, as the proposed model promotes fairness and well-being by ensuring an equal distribution of workload among employees. The proposed model takes into account the impact of sustainability decisions on employees, such as job opportunities and workload intensity. In addition, the proposed model places significant emphasis on promoting remanufactured products to reduce community pressure. This practical, actionable approach directly contributes to resource efficiency and sustainability. While previous models may acknowledge remanufacturing, they often focus more on conceptual or strategic frameworks and lack specific operational guidelines as the proposed model does.

III. Proposed sustainable business model

A. Close-loop knowledge business model

A comparison of the proposed model (Figure 1) with other models reveals its distinctive integration of sustainability, circular economy principles, and corporate strategy, which collectively serve to redefine industrial processes. This integration is a key factor in enabling companies to achieve comprehensive solutions and enhance operational efficiency upon adopting the model. Indeed, the model enables companies to make informed, sustainable decisions by aligning sustainability with strategic business objectives. It also offers a framework for reorganizing processes and optimizing resources, ultimately leading to enhanced performance. The following sections will demonstrate how companies can apply this model and make sustainability-driven decisions to achieve long-term success.

B. Key Performance Indicators for measuring sustainability

Key Performance Indicators for sustainable performance refer to measurable metrics used to evaluate a company's performance in achieving sustainability goals across the three pillars: economic, environmental, and social sustainability. By measuring performance, companies can identify areas for improvement and hold themselves accountable for progress toward sustainability targets. This ensures continuous enhancement in processes like resource use, waste reduction, and emissions control.

Various methods have been proposed to evaluate a company's sustainability performance, including product life-cycle analysis [1], sustainability performance assessment [5] and corporate social responsibility [4]. However, these methods can be challenging to implement due to their broad scope, data requirements, and reliance on multiple indicators. A well-defined framework provides clear, consistent, and reliable metrics to help companies make informed decisions about sustainability. It links sustainability goals to measurable outcomes, allowing managers to assess the effectiveness of sustainability initiatives. Therefore, integrating sustainable economy and sustainable manufacturing into business processes, exploring the impact of different processes on manufacturing under a sustainable framework, and developing measurement methods that help companies achieve continuous progress more effectively is critical [15].

IV. Application on Case Study: Medical Device Manufacturing Company

The objective of this section is to apply the theoretical concepts to practical situations by means of a case study. The focus of the case study from a Chinese Medical Device is the implementation of selected indicators and the utilization of developed models for achieving sustainability.

A. Use case description

The case company is a Chinese medical goods original equipment manufacturer (OEM) that produces operational beds for customers in West Africa. Data describing the current process was obtained from the information system. Due to the complex political and economic situations, various manufacturing and re-manufacturing processes were deployed on a Hybrid Flexible Flow-shop from a Chinese factory. The business model of the case company encompasses all the value creation processes from product design, purchasing and production, to marketing & sales. The case company explore customers through summer fairs, and August, September and October are the peak demand period, each year. The worldwide competition is stiff, customers are sensitive to prices.

The sold goods are low-valued, high-volume, high-variety (on the color, size, and the types of accessories assembled, etc.) and good-quality medical beds. The company can produce original products, but also provide customized solutions. Operational beds are currently produced to orders. Maximum capacity limits the ability to satisfy all demands during peak seasons. Excessive inventory of materials has been built to mitigate side effects of supply disruptions. However, the obsolescence of materials, has taken up over 80% of stocks, leading to the main losses of this manufacturer.

The case company initially adopts seven value-adding processes (from "Design Process" until "End-of-life disposal Process"). BPMN is used to demonstrate current activities in the manufacturing process. As shown in figure 2, production is divided into nine main steps, covering three different task types, sample production (step N. 3), batch production (step N. 6) and re-manufacturing operation (step N. 8). For sample production, Delivery Time (DT) is considered to assign jobs and distribute resources to operation. Apart from Delivery Time (DT), they consider Percent of Defective Product (PDP) to assign jobs and distribute resources to batch production and re-manufacturing operation. Indeed, for these kinds of production inspection, and sometimes touch up, are needed.

B. Evaluation

The well-known DMAIC (Define, Measure, Analyze, Improve, Control) approach is used to measure, improve and manage sustainability performance in a Chinese medical device case study.

1) Define: This phase involves identifying the problem or objective related to sustainability performance. It includes defining what needs to be improved, setting sustainability goals, and identifying key performance indicators (KPIs) to

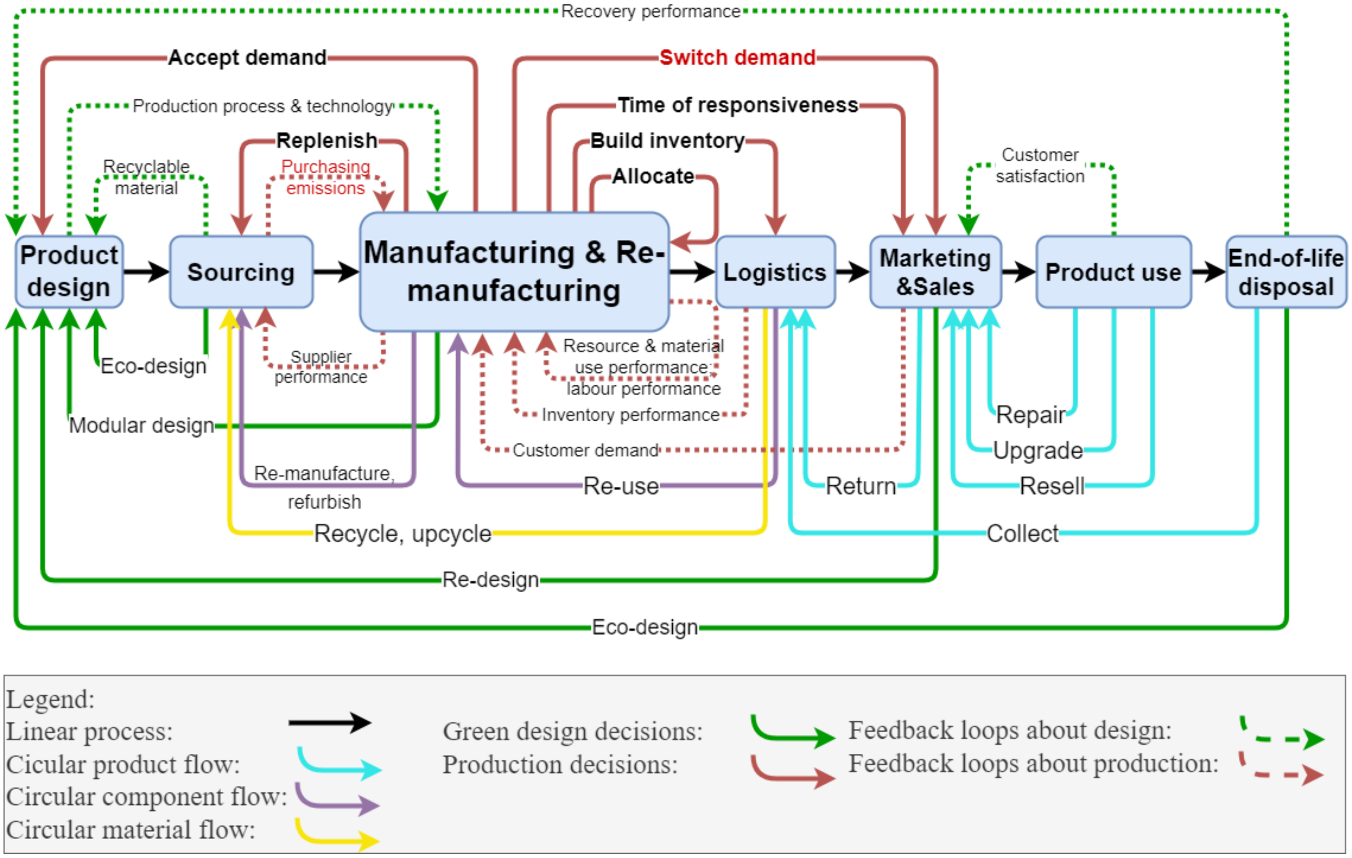

Fig. 1. Proposed close-loop knowledge sharing business model for sustainable management systems

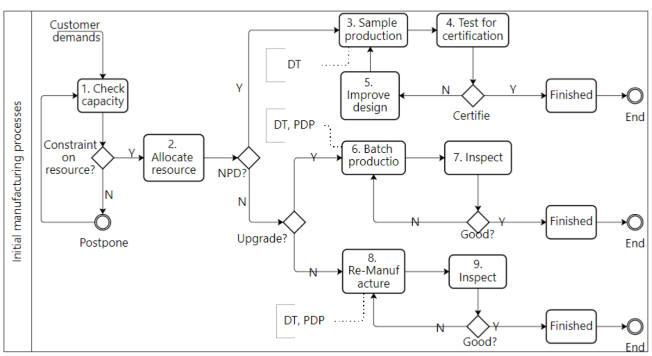

Fig. 2. Initial manufacturing processes

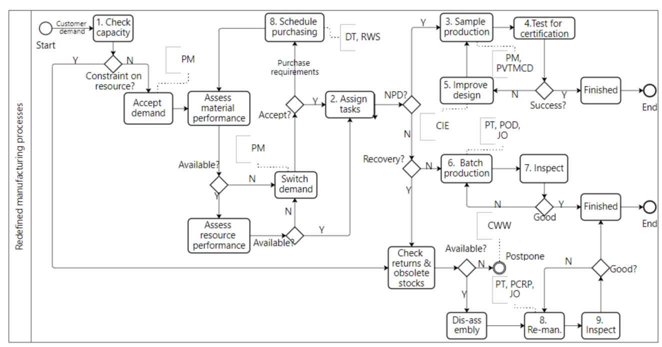

Fig. 3. Redefined manufacturing processes

measure success. Diverse issues that endanger the company have been found. The company currently produced to orders. The availability of resources (machines and labors), however, limits the ability to satisfy all needs during peak demand seasons. Excessive inventory of material leading to extra costs and waste is also observed.

- **Adding sustainable development decisions:** according to the business model we proposed, several sustainable issues were added, such as whether to accept customer needs, evaluate the quality of raw materials before assigning tasks, and evaluate the resources (machines and labor) to reduce the waste of resources caused by stopping production midway.

- **The choices of sustainability KPIs:** current KPIs (see Figure 2) are only depicting the economic performance of the manufacturing process, for instance, material cost and delivery time. The choice of sustainability KPIs from Sustainability Evaluation Factors literature for each process are more associated with operational success and efficiency of business.

- **Recommended measurements of selected KPIs for decision-making:** linkages between issues of case company and non-value adding processes have been analyzed, based on the developed models (Figure 1). A series of significant decisions that support to obtain solutions based on redefined manufacturing process to achieve sustainable development and efficiency improvement ultimately.

2) Measure: In this phase, the current state of sustainability performance is measured by implementing the KPIs defined earlier. It is essential to collect data that accurately reflects the current sustainability performance of processes or products.

3) Analyse: This phase focuses on analyzing the collected data to determine the root causes of sustainability performance issues. It involves identifying the relationship between actions and their effects on sustainability performance.

Considering inefficiencies in current business activities and operating processes of case company, a variety of sustainable sub-processes should be added into each process to pursue an operational success and efficiency.

- *From the strategic level:* the choice of demand identified to be satisfied should be added to existing business processes basically because it is difficult for case company to fully satisfy all customer demands, constrained by capacity. After customer demands are identified, the choice of accepting demands is highly associated with profits [6]. Other demands that are less likely to get orders or bring profits should be declined, hence. The level of inventory should be built for significant demands that cannot be fully satisfied during peak seasons under capacity constraint.

- *From the operational level:* production should be planned and updated with information updating about resource, material and inventory performance. Currently, material unavailability and quality problems cause schedule infeasible and production disruptions. Data on purchasing performance is needed to assure on-time delivery. This information-sharing sub-process is therefore added to the proposition. Product-dependent procedures with job shop layouts make workload balance more difficult. Since the state of machines is different, the choice of source may affect production speed and the number of buffers required. The sub-process of assessment of resource performance is added to the proposition for resource allocation. When components and resources are insufficient to respond to demand changes, other solutions can be provided to switch demand instead of increasing inventory pressure or purchasing emissions.

4) Improve: Based on the analysis, specific improvement actions or projects are developed and implemented, as is shown in figure II. This phase aims to redefine manufacturing processes by adopting our proposed business model, and obtain end-to-end solutions to meet sustainability objectives.

The comparison highlights clear improvements in profitability, operational efficiency, environmental performance (especially in the reuse of components), and supplier collaboration after adopting sustainable development practices. These changes suggest that sustainability initiatives have positively impacted both economic performance and environmental responsibility. However, areas such as product quality (defective product rates) and communication with suppliers may still require further focus to fully align with sustainability goals.

5) Control: The final phase ensures that the improvements are maintained over time. Monitoring systems are put in place to control the new processes and to ensure continuous improvements in sustainability performance.

V. Applying the DMAIC Method and Sustainability Indicators to a Real Case

The final objective was to apply the DMAIC (Define, Measure, Analyze, Improve, Control) method and the selected KPIs to analyze and improve the business processes of a case company. The paper applies the DMAIC methodology to a Chinese medical device manufacturer, demonstrating how sustainability indicators can be used to enhance operational processes.

- **Define**: In this phase, the paper identifies the major operational issues facing the case company, such as resource shortages during peak demand periods, excessive inventory, and quality problems. Sustainability goals are defined in terms of reducing waste, improving efficiency, and enhancing collaboration across the supply chain.

- **Measure**: The existing manufacturing process is enhanced by adding sustainable development decisions: demand-acceptance, demand-switching, resource performance evaluation, etc. These changes not only align the manufacturing process with the goals of sustainability but also improve its operational efficiency by making the model more adaptive to real-time data and disruptions. By integrating sustainable KPIs into manufacturing-related decision-making processes, the paper enhances the system's ability to address challenges such as resource shortages, production disruptions, and environmental impacts. Thus, the objective of redefining manufacturing process is thoroughly addressed. Then, the KPIs selected in the earlier stages are used to measure the current performance of the company's operations. For example, indicators like the percentage of reused components and the percentage of defective products provide measurable insights into the company's environmental

Sustainability indicators	Measurable KPIs	Before	After
Economical dimension			
PM	Profitability (%)	22.44%	**23.10%**
DT	Percent of late delivery (%)	14%	**3%**
Environmental dimension			
PCRP	Percent of reused components in product (%)	4.91%	**11.09%**
PVTMCD	Variation between varied products and standardised products	1.06	**1.89**
POD	Percent of defectives (%)	6%	6%
Social dimension			
CIE	R&D team's waiting time for feedback (days)	7	**3**
CWW	Customer's acceptable waiting time for products (days)	20	20
RWS	Company's waiting time for supplier response (days)	7	7
JO	Number of employees recruited per day on average (persons)	111.79	**40.83**

TABLE II

COMPARISON OF SUSTAINABILITY PERFORMANCE BEFORE AND AFTER ADOPTING OUR PROPOSED SUSTBM

and quality performance.

- **Analyze**: The analysis phase reveals that the company suffers from inefficiencies due to outdated business processes and poor collaboration with suppliers. By using the selected KPIs, the paper identifies bottlenecks and areas for improvement, particularly in terms of resource use and production scheduling.

- **Improve**: The paper suggests actionable improvements, such as adopting modular product designs, closer supplier collaboration, and improving the re-manufacturing process. These improvements are aligned with the KPIs and are aimed at enhancing the company's sustainability performance.

- **Control**: Finally, the paper outlines the steps necessary to control and maintain these improvements over time. This involves continuous monitoring of the KPIs and adjusting processes based on real-time data to ensure ongoing sustainability gains.

By successfully applying the DMAIC method and the sustainability KPIs to the case study, the paper demonstrates the practical applicability of its proposed framework, fulfilling the fourth objective.

VI. CONCLUSION AND FUTURE DIRECTION

This paper focuses on the critical issue of sustainable manufacturing, addressing the need for integrating sustainability into operational processes within the manufacturing industry.The increasing global emphasis on environmental preservation, resource efficiency, and social responsibility has rendered sustainable manufacturing a major concern.However, there are significant challenges, particularly in selecting suitable sustainability indicators and integrating them into the operational level, such as the manufacturing process. This research endeavored to address these gaps by developing a methodology that selects relevant sustainability indicators and applies them to enhance the business and production models of a Chinese medical goods company.

A significant contribution of this paper is the development of a pragmatic methodology for selecting sustainability indicators relevant to operational processes, by emphasizing economic, environmental, and social dimensions, the methodology assists companies in identifying indicators that will most effectively drive improvements in resource use, waste reduction, and overall sustainability performance.The paper implements the selected sustainability indicators to transform a conventional linear business model into a circular and sustainable one. This transformation exemplifies how companies can transition from linear production processes to more resource-efficient, circular models that are aligned with sustainability objectives.The paper enhances the manufacturing process by incorporating sustainable development decisions, enabling the manufacturing process to cope with dynamic production environments more effectively, thereby enhancing both operational efficiency and sustainability outcomes.

By employing the DMAIC (Define, Measure, Analyze, Improve, Control) approach, the paper showcases the practical implementation of the proposed sustainability framework. This structured approach ensures that the changes are measurable and controllable, providing a clear pathway for other companies to follow.

However, while the case study validates the short-term effectiveness of the proposed model, long-term impacts require continuous monitoring and adjustments. Future research endeavors must prioritize the long-term sustainability performance of the proposed model, exploring its capacity for evolutionary adaptation to evolving market conditions, technological advances, and regulatory requirements.

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