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Circular Supply Chain Planning: Balancing New and Recovered Product Demand in Production Scheduling

Sahil Bansal

Senior Manager Supply Chain and Analytics
sahilb@umich.edu

Abstract:
The transition from linear to circular supply chains necessitates fundamental changes in production scheduling, particularly when manufacturers must simultaneously fulfil demand for new products and recovered (remanufactured) products. This paper presents a conceptual framework for integrated production scheduling that balances new and recovered product streams while managing demand cannibalisation, uncertain return flows, and shared capacity constraints. The framework introduces a Demand Cannibalisation Index (DCI) that quantifies the substitution effect between new and recovered product demand, enabling planners to make informed scheduling trade-offs. Drawing on closed-loop supply chain literature and production planning theory, this paper identifies key planning challenges, proposes a practitioner-oriented scheduling framework, and outlines managerial implications for manufacturers pursuing circular economy strategies. The framework is validated through an illustrative case in the consumer electronics sector, demonstrating its applicability to real-world production environments.

Keywords: Circular supply chain, production scheduling, remanufacturing, demand cannibalisation, closed-loop supply chain, recovered products, capacity planning

1. Introduction

The circular economy model has gained significant momentum as organisations seek to minimise resource consumption, reduce waste, and extend product lifecycles [1]. Unlike the traditional linear model of "take, make, waste," a circular supply chain recovers end-of-life products and reintroduces materials and components back into the production system through reuse, refurbishment, and remanufacturing [2]. This transition creates a fundamental planning challenge: production schedulers must now balance two interdependent demand streams — new products manufactured from virgin materials and recovered products restored from returned goods — within shared capacity environments.

Remanufacturing, defined as the process of restoring end-of-life products to like-new condition with equivalent performance warranties [3], has emerged as a substantial value recovery mechanism within circular supply chains. Research indicates that firms can recover 70–80% of product value through remanufacturing, significantly reducing procurement costs for virgin materials [4]. However, the introduction of remanufactured products into the market creates a demand cannibalisation effect, where recovered products substitute for new product purchases, complicating demand forecasting and production planning [5].

Traditional production scheduling assumes a single product stream with predictable demand patterns. Circular supply chain planning introduces three additional complexities: (a) uncertain timing and quality of product returns, (b) demand substitution between new and recovered products, and (c) shared manufacturing capacity between forward and reverse production flows [6]. These complexities are insufficiently addressed by existing production planning frameworks, which tend to treat forward and reverse supply chains as independent systems [7].

This paper addresses the following research question: How can manufacturers develop an integrated production scheduling framework that balances new and recovered product demand while managing cannibalisation effects and capacity constraints?

The contribution of this paper is threefold. First, a conceptual framework is proposed that integrates forward and reverse production scheduling under shared capacity constraints. Second, the Demand Cannibalisation Index (DCI) is introduced as a practical metric for quantifying substitution effects between product streams. Third, managerial guidelines are provided for implementing circular production scheduling in practice.

The remainder of this paper is organised as follows. Section 2 reviews relevant literature on circular supply chains, remanufacturing planning, and demand cannibalisation. Section 3 presents the proposed framework. Section 4 provides an illustrative case application. Section 5 discusses managerial implications. Section 6 concludes with limitations and future research directions.

2. Literature Review

2.1 Circular Supply Chain Management

Circular supply chain management (CSCM) involves the configuration and coordination of organisational functions to close, slow, intensify, narrow, and dematerialise material and energy loops [8]. The concept extends beyond traditional reverse logistics by emphasising proactive design for circularity rather than reactive waste management. Geissdoerfer et al. [9] noted that CSCM "remains a rather unexplored area of research," particularly regarding its implications for production planning and scheduling.

The Ellen MacArthur Foundation [10] identified three principles driving circular economy implementation: eliminating waste and pollution, circulating products and materials at their highest value, and regenerating natural systems. For manufacturing firms, these principles translate into operational requirements for production systems that can simultaneously handle new product manufacturing and recovered product restoration.

Stahel [11] introduced the concept of product-life extension as a competitive strategy, arguing that reuse and remanufacturing create economic value while reducing environmental impact. This perspective has significant implications for production scheduling, as extending product lifecycles through remanufacturing introduces a secondary demand stream that competes with new product manufacturing for shared resources.

2.2 Production Planning in Closed-Loop Supply Chains

Closed-loop supply chains (CLSC) integrate forward and reverse material flows, requiring coordination between manufacturing and remanufacturing operations [12]. Guide and Van Wassenhove [13] established foundational principles for CLSC management, emphasising the need to match return types with appropriate recovery processes.

The production planning challenge in CLSC environments is characterised by three sources of uncertainty: return timing, return quality, and demand for recovered products [14]. Wei et al. [15] demonstrated that these uncertainties create significant planning complexity, as production schedulers must simultaneously manage virgin material procurement, return collection, disassembly scheduling, and remanufacturing operations.

Kenné et al. [16] developed production planning models for hybrid manufacturing–remanufacturing systems, showing that optimal policies depend on the interaction between return rates, remanufacturing yields, and demand patterns. Their work highlighted the importance of dynamic capacity allocation between new and remanufactured product lines.

2.3 Demand Cannibalisation in Remanufacturing

Demand cannibalisation occurs when recovered products substitute for new product purchases, reducing the net market size for new products [17]. Ferguson and Toktay [5] demonstrated that the profitability of remanufacturing depends critically on the degree of cannibalisation between new and remanufactured products.

Atasu et al. [18] examined the conditions under which manufacturers should offer remanufactured products alongside new products, finding that cannibalisation effects are moderated by product differentiation, pricing strategies, and consumer willingness-to-pay for recovered goods. Their analysis showed that manufacturers can mitigate cannibalisation through strategic product positioning and quality differentiation.

Ovchinnikov [19] extended this work by examining revenue implications of remanufacturing under different market conditions, demonstrating that the optimal production mix between new and remanufactured products varies significantly based on return availability and demand elasticity.

2.4 Research Gap

While existing literature has extensively modelled the economics of remanufacturing and the design of closed-loop networks, limited attention has been directed toward the operational production scheduling decisions that manufacturing planners face daily [20]. Three specific gaps are identified in the literature. First, existing frameworks treat demand for new and recovered products independently, without providing integrated scheduling mechanisms. Second, cannibalisation effects are typically modelled at the strategic level but not operationalised for tactical production scheduling. Third, capacity allocation between forward and reverse production is often treated as a static decision rather than a dynamic scheduling problem. This paper addresses these gaps by proposing a practitioner-oriented framework that integrates these elements into a unified production scheduling approach.

3. Proposed Framework

3.1 Framework Overview

The proposed Circular Production Scheduling Framework (CPSF) comprises four interconnected modules: (1) Demand Integration Module, (2) Return Flow Estimation Module, (3) Capacity Allocation Module, and (4) Schedule Optimisation Module. These modules operate sequentially within each planning cycle but incorporate feedback loops for dynamic adjustment. Figure 1 illustrates the overall architecture of the CPSF, including the sequential flow between modules and the feedback mechanisms that allow dynamic re-calibration across planning cycles.

The framework operates on the principle that circular production scheduling is fundamentally a demand-supply matching problem complicated by two additional factors relative to linear production: return uncertainty and cannibalisation effects. By explicitly quantifying these factors and incorporating them into scheduling logic, planners can make informed trade-offs between new and recovered product manufacturing.

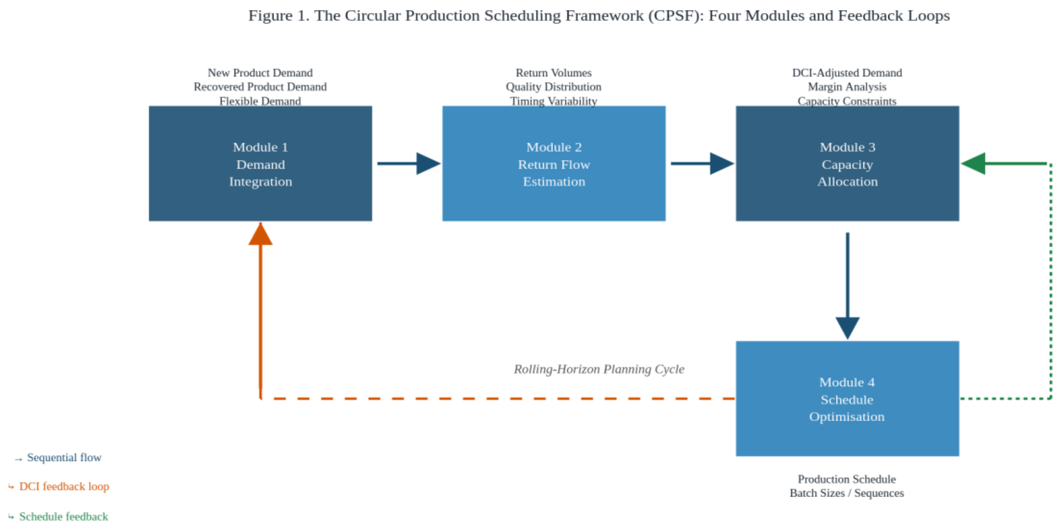

Figure 1. The Circular Production Scheduling Framework (CPSF): Four Sequential Modules with Feedback Loops

3.2 Demand Integration Module

The Demand Integration Module aggregates demand signals for both new and recovered products into a unified demand picture. Unlike traditional demand planning that considers only new product orders, this module incorporates three demand components. Primary new product demand (D_new) captures customer orders specifically requesting new products. Primary recovered product demand (D_rec) captures customer orders specifically requesting recovered or remanufactured products. Flexible demand (D_flex) represents customer orders that can be fulfilled by either new or recovered products, depending on availability, pricing, and promotion.

The critical insight is that flexible demand creates a substitution buffer that planners can exploit for capacity optimisation. When return flows are abundant, flexible demand can be routed to recovered products, preserving virgin material capacity for committed new product orders. This tripartite demand structure replaces the single-stream assumption of conventional scheduling and provides the foundational input for downstream modules.

3.3 The Demand Cannibalisation Index (DCI)

To operationalise the cannibalisation effect for production scheduling purposes, this paper introduces the Demand Cannibalisation Index. The DCI is formally defined as:

$DCI = (\Delta D_{new} \mid D_{rec} > 0) / D_{rec}$ … (1)

In this expression, ΔD_new represents the change in new product demand attributable to the presence of recovered product offerings, while D_rec represents recovered product demand in the same period. As illustrated in Figure 2, the DCI ranges from 0 to 1, where DCI = 0 indicates no cannibalisation (recovered products serve entirely new market segments) and DCI = 1 indicates complete cannibalisation (every recovered product sold displaces one new product sale). In practice, most manufacturing contexts exhibit DCI values between 0.2 and 0.6 [5, 18].

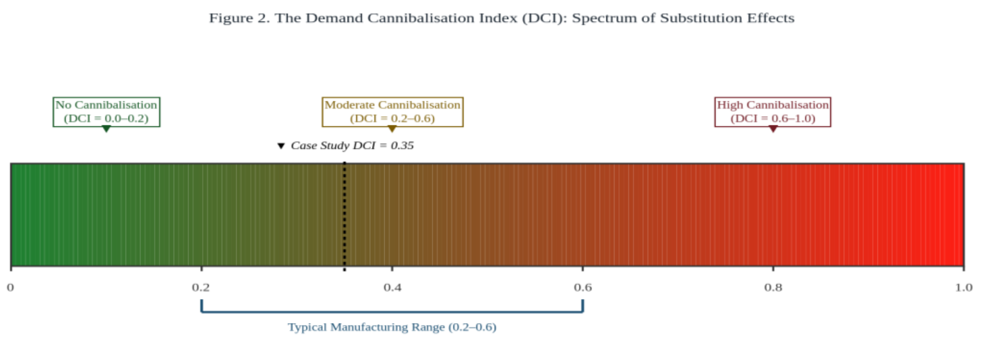

Figure 2. The Demand Cannibalisation Index (DCI): Spectrum from No Cannibalisation (0.0) to Complete Cannibalisation (1.0)

The DCI enables planners to estimate the net demand impact of scheduling decisions. When a planner increases recovered product output by X units, the expected reduction in new product demand is approximately X × DCI units, yielding a net market volume increase of X × (1 − DCI) units. This relationship transforms cannibalisation from a qualitative concern into a quantifiable input for production planning decisions.

3.4 Return Flow Estimation Module

Product returns represent the supply side of the remanufacturing equation. The Return Flow Estimation Module characterises returns along three dimensions: volume uncertainty, quality distribution, and timing variability. Volume uncertainty arises because the quantity of returns received in any period varies based on product age profiles, consumer behaviour, and collection programme effectiveness. Quality distribution reflects the variable quality levels of returned goods, with some units suitable for direct reuse, others requiring component-level remanufacturing, and some only suitable for material recycling. Timing variability refers to the lag between product sale and end-of-life return, which creates forecasting challenges for production schedulers.

Following the approach of Guide et al. [21], returns are classified into three quality grades as depicted in Figure 3. Grade A units require only minor refurbishment and contribute the least capacity demand. Grade B units need component replacement and intermediate processing. Grade C units require full disassembly and remanufacturing, carrying the highest capacity and time requirements. Each grade has different processing times, yield rates, and capacity requirements, directly affecting scheduling feasibility and batch planning decisions.

Figure 3. Return Quality Grade Classification System for Remanufacturing Scheduling

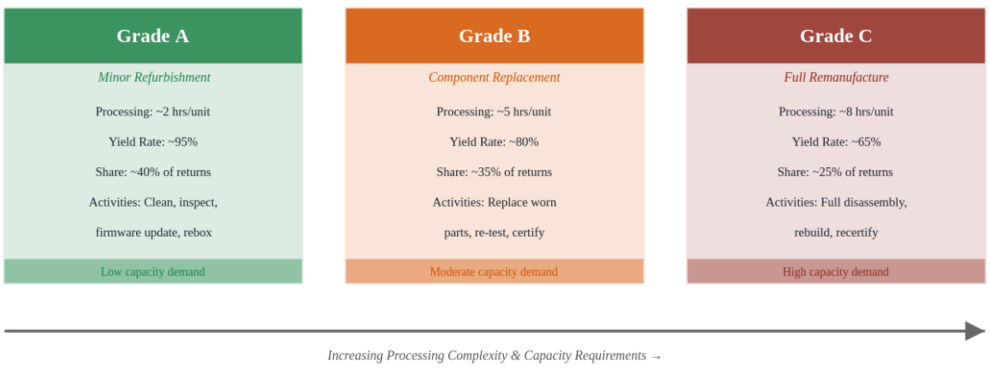

Figure 3. Return Quality Grade Classification System: Processing Requirements and Capacity Implications for Grades A, B, and C

3.5 Capacity Allocation Module

The Capacity Allocation Module determines how shared manufacturing capacity is divided between new product production and remanufacturing operations. This allocation decision is influenced by several interdependent factors: the relative margins of new versus recovered products, current return inventory levels and quality mix, DCI-adjusted net demand impact, contractual obligations and service level requirements, and setup time and changeover costs between production modes. The interaction of these factors determines the optimal capacity split for any given planning period.

The module recommends capacity splits on a rolling-horizon basis, updated each planning cycle as new demand signals and return flow data become available. This dynamic allocation approach contrasts with static capacity reservation policies common in practice, where a fixed percentage of capacity is permanently assigned to remanufacturing regardless of prevailing demand or return conditions. By enabling periodic reallocation, the framework captures the economic value of flexibility that is otherwise foregone under rigid allocation rules.

3.6 Schedule Optimisation Module

The Schedule Optimisation Module generates detailed production schedules that honour capacity allocations while maximising total value creation. The module incorporates sequencing rules for minimising changeover times between new and remanufactured production runs, batch sizing approaches for remanufacturing operations that account for quality-grade variability, coordination of disassembly, cleaning, inspection, and reassembly activities, and synchronisation of component availability from both virgin procurement and recovered parts streams.

The scheduling logic prioritises committed orders first, then allocates remaining capacity between flexible demand fulfilment and build-to-stock decisions based on DCI-adjusted demand projections. This priority structure ensures that contractual obligations are met while allowing the planner to exploit the demand flexibility buffer identified in the Demand Integration Module. Together, the four modules form a coherent and iterative scheduling system suited to the operational realities of circular manufacturing environments.

4. Illustrative Case Application

4.1 Context

To demonstrate the framework's applicability, consider a consumer electronics manufacturer producing smartphones. The firm sells new devices and operates a certified refurbishment programme that offers recovered devices at a 30% price discount. Monthly production capacity is 100,000 units, shared between new and refurbished production. The firm receives approximately 15,000 to 25,000 returns per month through trade-in programmes, providing a consistent but variable supply of raw material for its remanufacturing operation.

4.2 Application of CPSF

Applying the Demand Integration Module, monthly demand is found to comprise 70,000 units of committed new device orders, 12,000 units of committed refurbished device orders, and 20,000 units of flexible demand from customers choosing based on availability and promotional pricing. DCI estimation through historical demand analysis reveals a value of 0.35, indicating that for every 100 refurbished devices sold, new device demand decreases by approximately 35 units. This moderate cannibalisation figure reflects the distinct market segments served: price-sensitive customers who preference refurbished devices, and technology-focused customers committed to new product purchases.

The Return Flow Estimation Module characterises the firm's monthly receipt of an average of 20,000 returns with the following quality distribution: Grade A accounting for 40% of returns (approximately 8,000 units), Grade B accounting for 35% (approximately 7,000 units), and Grade C accounting for the remaining 25% (approximately 5,000 units). Processing times per unit are 2 hours for Grade A, 5 hours for Grade B, and 8 hours for Grade C, yielding a weighted average processing burden that directly informs capacity allocation decisions.

The Capacity Allocation Module, drawing on the demand structure and DCI estimate of 0.35, recommends allocating 72% of total capacity to new production (72,000 units) and 28% to remanufacturing (28,000 units). The 20,000 units of flexible demand are split 12,000 to new products and 8,000 to refurbished products based on margin optimisation and return availability. Figure 4 visualises both the overall capacity split and the distribution of flexible demand.

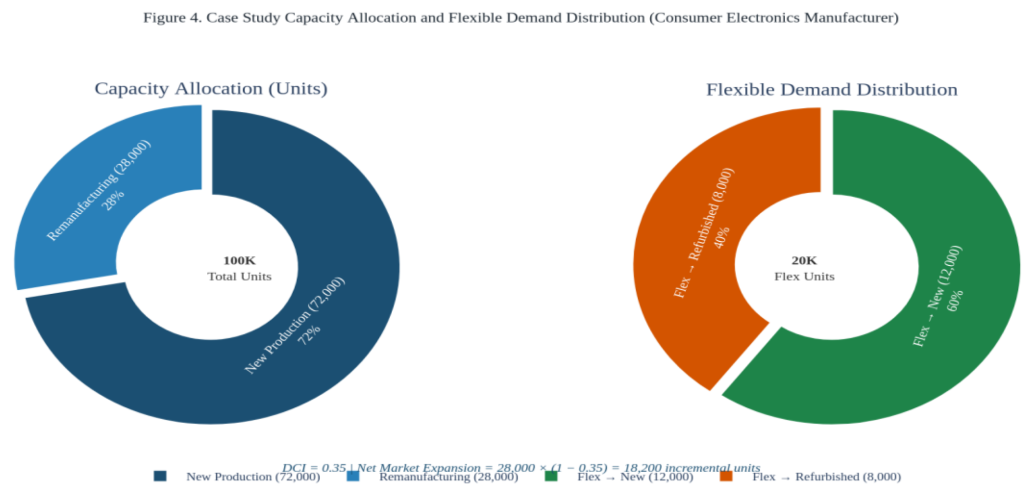

Figure 4. Case Study Capacity Allocation Split (72% New / 28% Remanufacturing) and Flexible Demand Distribution

The net impact assessment, performed by the Schedule Optimisation Module, confirms that the 28,000 recovered units generate a net market expansion of $28{,}000 \times (1 - 0.35) = 18{,}200$ incremental units, while simultaneously reducing virgin material consumption by 28,000 units worth of components. This dual benefit — market expansion through accessible pricing and resource efficiency through material circularity — exemplifies the value proposition that the CPSF is designed to make operationally tractable.

4.3 Results and Insights

The framework application demonstrates several practical insights that extend beyond the specific numerical parameters of this case. Explicit DCI quantification enables data-driven capacity allocation rather than arbitrary or convention-based production splits, improving the quality of scheduling decisions by grounding them in measurable demand dynamics. Quality-grade classification of returns directly influences scheduling feasibility and batch sizing, preventing over-commitment to remanufacturing when return quality is degraded. The flexible demand buffer provides scheduling resilience when return volumes fluctuate, serving as a shock absorber between uncertain supply and committed demand. Dynamic reallocation of capacity across planning cycles allows the firm to respond to seasonal return patterns, which in the electronics sector typically peak following holiday purchasing periods when trade-in activity intensifies.

5. Managerial Implications

5.1 Implications for Production Planners

The framework provides production planners with structured decision logic for balancing dual product streams. Rather than treating cannibalisation as a qualitative concern to be managed through judgment alone, firms should invest in demand analytics to quantify DCI for their specific product categories and market segments. Tracking recovered product sales alongside new product demand trends provides the data necessary to estimate and regularly update the DCI, enabling evidence-based scheduling decisions that adapt to changing market conditions.

Production schedules for remanufactured products should account for quality-grade variability in returns. Flexible batch sizing and modular scheduling approaches are preferred over fixed production run configurations, since the unpredictable mix of Grade A, B, and C returns makes rigid scheduling structures prone to under-utilisation or capacity overcommitment. Where possible, firms should cultivate a flexible demand segment that accepts either new or recovered products, as this segment provides scheduling freedom to optimise capacity utilisation across both production modes during periods of return volume uncertainty.

Static capacity splits between new and remanufactured production fail to account for seasonal return patterns and demand fluctuations. Monthly or bi-weekly capacity reallocation based on updated DCI estimates and return forecasts consistently outperforms fixed allocation policies. The overhead of more frequent reallocation reviews is modest relative to the capacity savings and margin improvements achievable through better alignment between return supply, cannibalisation-adjusted demand, and production commitments.

5.2 Implications for Supply Chain Strategists

At the strategic level, the framework highlights several considerations for firms transitioning to circular supply chains. The DCI framework reveals that cannibalisation exists on a spectrum rather than operating as a binary phenomenon. Firms can actively manage their DCI position through product differentiation, pricing strategy, branding of recovered product lines, and channel separation. A consumer electronics firm that brands its refurbished line under a distinct sub-brand with separate distribution channels will typically achieve a lower DCI than a firm selling refurbished devices through the same platform as new devices at a modest discount.

Superior collection and sorting capabilities increase both the volume and quality predictability of returns, directly reducing scheduling uncertainty in the Return Flow Estimation and Capacity Allocation modules. Firms that invest in take-back infrastructure, grading technology, and supplier relationships for recovered components gain a scheduling advantage that translates into more consistent remanufacturing throughput.

Finally, treating new product and remanufactured product scheduling as independent problems leads to suboptimal capacity utilisation. The value of integration increases as the share of recovered products in total output grows, making the CPSF increasingly economically significant as circular economy strategies mature within a firm.

6. Conclusion

6.1 Summary

This paper presented the Circular Production Scheduling Framework (CPSF) for balancing new and recovered product demand in manufacturing environments pursuing circular economy strategies. The framework addresses a critical gap in the literature: the lack of practitioner-oriented approaches for operationalising circular supply chain principles within production scheduling. The introduction of the Demand Cannibalisation Index provides planners with a quantifiable metric for managing substitution effects between product streams, while the four-module architecture of the CPSF translates the conceptual logic of circular production into actionable scheduling procedures.

6.2 Limitations

Several limitations merit acknowledgement. First, the framework is conceptual and validated through illustrative case application rather than empirical testing across multiple industries. The numerical parameters used in the consumer electronics case are illustrative rather than empirically derived, and generalisation to other manufacturing contexts requires industry-specific calibration. Second, the DCI is presented as a static ratio, whereas cannibalisation effects likely vary over product lifecycle stages and competitive conditions. A dynamic DCI that responds to market maturity, competitive entry of other remanufacturers, and consumer perception shifts would provide greater fidelity. Third, the framework does not explicitly address multi-product interactions where cannibalisation may occur across product families rather than within a single product category.

6.3 Future Research Directions

Future research should pursue several avenues. Empirical validation of the CPSF across manufacturing sectors, including automotive, industrial equipment, and medical devices, would strengthen generalisability claims and enable sector-specific parameterisation of the DCI. Development of dynamic DCI models that evolve with market conditions represents an important extension, potentially drawing on time-series demand decomposition or machine learning approaches to estimate cannibalisation elasticity as a function of pricing and product positioning variables. Investigation of multi-product cannibalisation networks, where recovered products from one category affect demand for new products in adjacent categories, presents a rich research opportunity at the intersection of marketing and operations management. Finally, integration of sustainability metrics, including carbon footprint reduction and material circularity indicators, into the scheduling objective function would align the framework with broader circular economy assessment standards and enable planners to simultaneously optimise economic and environmental performance.

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