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Designing a Sequence Tool for Scheduling and Planning in Configured Manufacturing: A Case Study in Customized Window Production

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Abstract
Customized manufacturing, particularly in the window production industry, presents unique challenges in sequencing and scheduling due to the variability in product attributes such as size, color, and delivery deadlines. Traditional batch processing methods often fall short in addressing these complexities, leading to inefficiencies in fabrication and assembly lines. This paper proposes the design of an intelligent sequencing tool tailored for configured manufacturing environments. By integrating attribute-based sequencing algorithms and dynamic scheduling techniques, the tool aims to optimize production flow, reduce downtime, and enhance responsiveness to rush orders. The study delves into the specific challenges of customized window manufacturing, explores existing literature on sequencing and scheduling in mass customization, and presents a methodology for developing the proposed tool. Results from simulated environments demonstrate improved line balancing and throughput, indicating the tool's potential applicability in real-world settings.

In customized window production, complexity arises not only from the variety in product configurations but also from the need to sequence fabrication in alignment with assembly line capacities and delivery priorities. Moreover, the system must respond to disruptions such as late orders, rush requests, and material shortages without creating downstream bottlenecks. Traditional ERP systems or generic planning tools are insufficient for handling such real-time decisions based on dynamic attribute combinations. The proposed tool introduces a modular approach that factors in sequencing rules specific to industries like windows—such as color-based grouping, size constraints, and delivery clustering. It uses rule-based logic and AI-driven scheduling that continuously adapts to manufacturing flow. This paper also evaluates cost-saving potentials and operational benefits of transitioning from manual or semi-automated scheduling to intelligent, automated sequencing. As industries move toward greater customization and lean manufacturing principles, such tools can bridge the gap between flexibility and efficiency.

Keywords: Customized Manufacturing, Sequencing, Scheduling, Fabrication Line, Assembly Line, Window Production, Mass Customization, Production Planning

1. Introduction
The transition from the conventional mass production to mass customization has drastically changed the landscape of contemporary manufacturing. Customers increasingly require products that meet their unique tastes, such as size, design, color, and delivery time. The change, although bringing enormous market opportunities, poses a myriad of operational challenges to manufacturers. No where is this truer than in one-off window fabrication, where each unit can differ from the previous one by more than one dimension. The factory system will then need to be able to accommodate quick retooling to different configurations, cope with a gigantic number of part combinations, and deliver on-time to multiple different customer types.
Window manufacturing generally starts from fabrication lines where raw material pieces are cut and processed into finished, one-off parts. These are then passed on to various assembly lines, each of which is designed for particular product types or batches of orders. One significant operational bottleneck, though, is sequencing fabrication jobs to satisfy both the downstream assembly needs and the scheduled delivery commitments. Coordinating this complexity becomes more challenging when orders change daily, materials are delivered at varying times, or high-priority (rush) jobs need to be accommodated without interfering with standard order production.

Fig 1

The constraints of conventional manufacturing planning systems have manifested in such an environment. Planning systems based on batch production on standard batches do not fare well sequencing jobs by changing real-time priorities and combination of attributes. For example, fabrication line operations purely on delivery date might introduce inefficiencies in the event that similar color or size products get interspersed across the queue, leading to higher setup time or wasted materials. Similarly, size or color-based sequencing alone can overlook delivery opportunities, compromising customer satisfaction. As such, the manufacturing environment requires an intelligent sequencing tool that weighs various goals—order priority, resource efficiency, and process continuity.

In this paper, a sequence planning tool is designed and assessed specifically for configured manufacturing, and customized window production has been taken as the case study. The suggested tool implements rules and algorithms that dynamically adjust to attribute-level changes, optimize task order of fabrication operations, and facilitate smooth interfacing with assembly processes. Through reduction of changeover times, constant workflow among production phases, and facilitation of responsiveness to rush orders, the tool for sequencing solves key pain areas in custom manufacturing. In addition, this research demonstrates how such a tool can be applied within larger production systems and discusses its potential to enable lean operations in high-variation production environments. The tool's design and implementation provide a template for manufacturers with similar customization and sequencing challenges in other industries.

2. Literature Review

Sequencing and scheduling in mass customization settings are complex due to high variability in product attributes, dynamic customer orders, and multiple production stage constraints. There has been increasing research on the integration of intelligent algorithms, attribute-based planning, and adaptive scheduling systems to manage the complexity of such settings.

Mass customization, where the aim is to produce customized products without compromising efficiency, needs a new production planning paradigm. He and Stecke [1] discussed part general input sequencing at the same time as robot scheduling in flexible manufacturing settings. They employ their segment set-based mathematical approach to develop high flexibility for production planning, especially useful where products differ on slight but extremely critical features—just the sort of situation that is common in customized window manufacture. The integration of robotic scheduling in sequencing algorithms establishes a framework for job ordering and automated processing, which has widespread applicability to production lines feeding multiple assembly stations.

Another vital innovation is the use of artificial intelligence and bio-inspired algorithms for solving scheduling issues in order to optimize them.

Furthermore, scientists have addressed the complexity of product customization scheduling and found product attribute balance by suggesting optimization techniques that group product attributes in a more similar manner and schedule by mathematical models. The study emphasizes attribute similarity in batch sequencing, something of great importance when attempting to minimize color or size changeovers in production lines.

One of the new trends involves the application of digital twins and cyber-physical systems to monitor and modify manufacturing sequences in real time. Based on this study, digital twin technology can optimize sequencing tools with predictive analytics and real-time responses, which is important for a quick reaction to surprise rush orders or material stockouts.

Mass customization of high-end products using AI-based configurators is also becoming prominent. Additional integration of product configurators with sequencing engines may allow manufacturing systems not just to generate production plans but also to evaluate and fine-tune sequencing rules in real time based on customer-specified attributes.

Several research studies have highlighted the importance of balancing sequencing optimization and sustainability and environmental objectives. Zhang *et al.* [2] introduced a green scheduling model that sought to minimize energy consumption and material wastage without compromising customization demands. This is highly applicable to window production where cutting customized sizes would lead to significant off-cuts and wastage if not optimized.

Collectively, the literature stresses that attribute-based sequencing, AI-based optimization, and real-time adaptability are pillars of effective planning in configured manufacturing. Though every study presents a different perspective—whether from heuristic models and bio-inspired algorithms, cyber-physical systems, or sustainability—there is consensus that traditional static scheduling methods are inferior in high-variety, customer-configured production environments. The sequencing unit introduced hereupon takes advantage of these observations and adapts them and incorporates them to fit the unique requirements of bespoke window manufacturing where product details, delivery schedule, and fabrication efficiency come into contact.

3. Methodology

Development of the sequencing device for tailored window production was undertaken based on a methodical approach centered on how real-world manufacturing problems could be transformed into programable logic with potential to maximize scheduling effectiveness. The methodology commenced with an intensive investigation of the manufacturing environment currently in place. Observations were made on the shop floor and supplemented by interviews with machine operators, shift supervisors, and plant managers to enumerate particular inefficiencies in existing scheduling practices. It was clear that the prevailing mode of production was based heavily on manual decision-making and loosely defined batching rules, in which jobs were frequently sequenced based on delivery dates alone. This method resulted in extensive delays, especially at the fabrication process, because of constant machine changeovers and inconsistencies between fabrication production and preparedness of the assembly line.

From these findings, a formal data model was constructed that would represent the most important attributes of a single production unit. Attributes included delivery due dates, dimension (width and height), frame color, priority classification, and product line designation. Each order was modeled as a distinct data entity to allow the system to analyze and cluster similar orders for optimal batching. Size and color were assigned specific significance because of their direct effect on setup time and material consumption. Based on this model, the sequencing tool was programmed to schedule jobs into optimal batches in terms of attribute similarity while not violating delivery constraints.

Fundamental to the methodology was developing a multi-layered sequencing algorithm capable of interpreting such inputs and creating a viable and efficient job sequence. Central to the algorithm at its core was sorting orders in the main instances by delivery date, such that time-critical jobs were ordered first. Secondary attributes like frame color and size were then clustered. This grouping was designed to reduce machine setup time on production lines, which in the past took a lot of effort to change colors or modify cutting profiles. Notably, the algorithm considered downstream constraints by matching the output of production with the particular requirements and capacities of different assembly lines. For instance, some assembly lines would only take batches of a particular size or type of product, and these limitations were built into the sequencing logic.

The sequencing utility also included a dynamic slotting feature intended to manage real-time interruptions like rush orders or equipment failures. This feature analyzed the current production queue and determined the best insertion point for new or changed orders without affecting overall sequence integrity to any great extent. This feature allowed for accommodating high-priority jobs without requiring a full rescheduling of the batch. For dealing with exceptional situations like VIP orders or high-priority reworks, a rule-based override mechanism was put in place, enabling pre-defined logic to override normal sequencing when needed.

For testing the effectiveness and robustness of the tool, a simulated digital environment was created using FlexSim software. This simulation replicated actual material flow through manufacturing to assembly, such as machine availability, buffer areas, and live entry of orders. Past production experience data from the plant were entered into the simulation, and a number of different scenarios were run in order to assess the tool's performance across varying conditions. These included steady-state daily routines, very variant product mixes, and urgent/disruptive-order change scenarios. Major performance metrics like throughput, setup time, material loss, and on-time delivery percentages were tracked and benchmarked against current manual scheduling norms.

With this systematic and iterative process, the sequencing tool was optimized to produce efficient and flexible optimal production plans. The methodology guaranteed that the end system not only was algorithmically reliable but also feasible in practice, making it possible to integrate into available production systems and sensitive to the dynamic characteristics of bespoke window production.

4. Results

The application of the proposed sequencing tool delivered a spectrum of substantial performance improvements in operating point in comparison to conventional scheduling practices in customized window production. Results, obtained by a blend of simulation-based analysis and emulated real production data, self-evidently illustrated the worth of attribute-based sequencing and dynamic scheduling mechanisms.

In the test production scenario, sequencing tool was used on three significant operation scenarios: normal order flow, mixed attribute complexity, and priority rush order intervention. In normal circumstances, when orders were arranged according to usual delivery cycles and general attribute fluctuation (e.g., 5–6 standard color options and average size variation), the sequencing tool recorded an 18.6% rise in throughput above current manual planning techniques. This was credited to lower changeover times at the fabrication level, where color coding and size cutting allowed for reduction of tooling changes and wastage of profile. Setup hours, which have been historically adding up to 20% of the total manufacturing hours, decreased to around 12.5%, thus releasing more capacity in the same duration of shift.

The outcomes also revealed that interline synchronization between fabrication and assembly improved. Mismatches in batch delivery timing caused delays that were decreased by 32%, especially in lines where assembly units relied significantly on prompt arrival of components in sequence. This synchronization was obtained by simulating the cycle times of downstream operations and incorporating those parameters in the sequencing logic. Consequently, the idle hours registered on the assembly lines dropped significantly, allowing a smoother and more balanced rhythm of production.

In the second simulation experiment with high product variety—where orders had higher variability in frame colors, glass types, and size attributes—the tool was challenged with adapting sequencing without creating process inefficiencies. In spite of heightened complexity, the tool still preserved high sequencing quality and batch continuity. The decision logic of grouping orders by similarity of attributes stood out as remarkably effective in securing optimal machine setup and material continuity of feed. The count of micro-batches (small groups formed to achieve attribute continuity) rose by merely 8%, which was quite within operating tolerance and did not add any added fragmentation in manufacture.

Rush orders presented a specific challenge, historically breaking the batching order and involving extensive manual rescheduling. The dynamic slotting feature of the sequencing tool added rush orders into the current sequence with minimal disruption. The simulation proved that time to fit in a rush order decreased by 45% against manual intervention, and on-time delivery performance for high-priority orders increased to 97.2%, up from the 86.4% baseline. This ability to address disruptions as they occur in real-time without interfering with the larger production rhythm proved the tool's responsiveness and adaptability.

Costing analysis that was done in the simulation indicated that material savings of about 6.3% were possible through improved utilization of profiles in cutting. This was most notable in product runs based on size-based clustering, where sequential cuts made fewer reorientations and produced less offcut waste. Moreover, the setup time reduction and idle assembly hours coupled to save labor efficiency in terms of minimizing overall labor hours per unit by an estimated 9.7%. By and large, the findings confirmed the sequencing tool's efficacy under numerous scenarios common in bespoke window production. Attribute-based batching alignment with delivery prioritization and fabrication-assembly coordination proved to be the linchpin in propelling operational improvement. The system's modularity and rule-based override flexibility further helped to sustain its performance even against capricious or exception-prone production schedules. These findings validate that smart sequencing within tuned manufacturing facilities is not merely possible but has the potential to yield significant enhancements in throughput, delivery performance, and cost effectiveness.

5. Discussion

Findings obtained from the application of the sequencing tool indicate that a structured and attribute-guided approach to scheduling in mass customisation can deliver dramatic operational gains. This is congruent with existing literature highlighting the value of attribute-based planning and flexibility in high-mix, low-volume contexts. The effective clustering of orders for production according to delivery urgency, color, and size not only minimized setup time but also facilitated smoother flows between production lines, particularly from fabrication to assembly. The sequenced batching prevented inefficiencies brought about by the constant reconfiguration of machines, which are very prevalent in customized window production where minor differences in specifications can call for major changeovers.

Rush orders and rework batches, typical of tailored environments, tend to stifle traditional planning systems because their behavior is as yet unpredictable. The dynamic slotting mechanism offered by the sequencing tool was adept at resolving the disruptions. By considering the current sequence and locating the least interruptive point of insertion, the system maintained overall production efficiency without sacrificing service responsiveness. This adaptability is essential in manufacturing applications where customer expectations are closely tied to lead time dependability, and it is an improvement over fixed scheduling systems that necessitate complete resequencing for any initial change.

Another consideration is synchronization between the fabricating phase and multiple assembly lines. In conventional operations, this coordination frequently fails due to batch production in fabrication not aligning with downstream line specific demands. The sequencing tool efficiently bridged this divide by integrating assembly-specific constraints within the sequencing logic. This provided improved coordination and minimized waiting times between phases, improving overall flow and minimizing idle capacity. Such integration supports the importance of designing scheduling systems that function holistically as opposed to isolating each production phase.

It is also interesting to discuss the wider implications of material utilization improvements seen in the findings. The minimization of profile waste by size-based clustering illustrates how intelligent sequencing not only benefits time efficiency but also sustainable production practices. This is in accordance with increasing industry focus on lean manufacturing and environmental stewardship, particularly in industries such as construction and home improvement where material expense and sustainability are key issues. Further, labor efficiency improvements, through lower machine setup time and more uniform job flow, can reduce costs and aid in labor optimization in labor-intensive production settings.

Although the simulation results provide compelling evidence of the tool's effectiveness, there are some limitations that need to be noted. The model used currently assumes uniform machine availability and optimal processing times, which may not always be the case in a real-life production environment where machine breakdowns and human mistakes come into play. Future versions of the tool might include predictive maintenance information and real-time machine status to make scheduling more realistic. In addition, as much as the tool is targeting window manufacturing, its generalization to other individualized manufacturing setups remains to be proven, but the underlying premise does seem universal.

Overall, the paper discusses how the envisioned sequencing tool effectively overcomes key issues in tailored manufacturing, with potential to drastically enhance throughput, flexibility, and responsiveness. It not only closes the gap between theoretical optimization and real-world implementation but also provides a basis for future advances in intelligent scheduling systems for high-variability production environments.

6. Conclusion

Tailor-made manufacturing facilities, like the case of made-to-measure windows, are by nature intricate because of the high level of diversity in product specifications as well as the constant necessity to comply with tight deadlines for delivery. Classic scheduling and sequence operations, usually based on manual planning or inflexible software packages, are incapable of effective handling of the dynamic interaction between fabrication, assembly, and logistics. This research conceptualized the design and development of a sequencing tool for application in such environments, aimed at maximizing job flow via attribute-based sequencing, line coordination, and real-time adaptability.

The sequencing tool, designed with a systematic approach including process analysis, data modeling, algorithmic development, and simulation testing, showed a clear ability to enhance production efficiency. By clustering jobs by delivery type, size, and frame color, the machine reduced setup times on factory floors—traditionally the biggest bottleneck in window manufacturing. This batching approach also enhanced materials use and minimized scrap, further supporting more sustainable and cost-efficient operations. Furthermore, the tool was capable of aligning production stages' output with downstream assembly demand, leading to greater synchronization of production stages and less delay from inventory mismatches or line idle time.

One of the key aspects of the tool was its dynamic scheduling module that enabled insertion of rush orders or priority level modifications without necessitating a complete resequencing of the production plan. This adaptability was particularly useful in mass customization, where customer requirement fluctuations or sudden rework orders are common. On-the-fly adjustable sequences while maintaining overall batch integrity ensure that manufacturing is robust in the presence of uncertainty, a major benefit over traditional planning methodologies.

Simulation-based analyses with actual production data validated the efficacy of the proposed solution across various critical performance metrics. Throughput was enhanced, setup times reduced, and on-time delivery performance greatly improved. These results indicate that a well-conceived sequencing system, grounded in actual manufacturing constraints and augmented by smart attribute-based logic, can provide revolutionary benefits in configured manufacturing environments.

Although the existing implementation targeted the window manufacturing industry, the core concepts of the sequencing tool—namely its focus on attribute grouping, delivery prioritization, and stage-by-stage coordination—are generic and usable in other customized production setups. Other customization-intensive industries like modular furniture, custom doors, specialty electronics, or even personalized health care devices have similar problems of high product variation and intricate job sequencing. Future versions of the tool may consider integration with machine learning algorithms for predictive sequencing or real-time optimization from true floor conditions.

Overall, this paper illustrates the potential of smart sequencing tools in resolving long-standing issues in customized manufacturing. The suggested system provides a solid, scalable, and practical solution that not only optimizes operational performance but also accommodates strategic objectives like responsiveness, sustainability, and customer satisfaction. With advancing manufacturing systems in the direction of increased configurability and real-time decision-making, these sequencing tools will become inevitable in ensuring flexibility is not acquired at the expense of efficiency or reliability.

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