# Event-Driven Order Rescheduling Model for Just-In-Sequence Deliveries to a Mixed-Model Assembly Line

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**Abstract.** Today's buyer markets and lean supply chains require build-to-order assembly systems with just-in-sequence (JIS) deliveries. Simultaneously production systems have become prone to supply disturbances (i.e. events) that endanger the synchronized delivery of all JIS components to the assembly line. To uphold production sequence stability, rescheduling is frequently required. Current methods, however, make assumptions that are often insufficiently aligned with real-world problems and focus on production issues while neglecting the implications of today's tight integration of supply chain with production processes. To this end, this contribution derives a general model of a mixed model assembly line. It then proposes and evaluates an event-driven rescheduling model for JIS deliveries. The results indicate that rework due to missing JIS components can be avoided without compromising performance.

**Keywords:** Just-In-Sequence, Mixed-Model Assembly Line, Rescheduling.

## 1 Introduction

Today's buyer markets have forced production systems to shift towards mass customization, where a large product portfolio and many customization options are key success factors for winning customer orders and improving competitiveness [9]. Thus, customer-specific products replaced standardized ones, in the course of which forecasting-based build-to-stock production strategies were abandoned in favour of build-to-order (BTO). It is a demand-driven production approach where a product is scheduled and built in response to a confirmed customer order [6]. Since neither demand volume nor product configurations can be anticipated, however, inventories for highly individualized, costly components were replaced with just-in-sequence (JIS) deliveries. Thus, today a customer order triggers the entire supply chain (SC) where several supply sequences of customer-specific components merge into one 'pearl chain' on an OEM's assembly line, which has two drawbacks. First, the

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production volume of the SC has to align itself with volatile customer demand, requiring flexible and responsive systems [3, 5]. Second, disturbances in JIS processes endanger the synchronized merging of all supply sequences at the OEM and the assembly of a customer-specific product from the respective components [1, 18].

This paper investigates the latter issue because today's global supply networks are prone to disturbances that range from deviations (e.g. transport delays) to disasters (e.g. floods) [2]. Through the seamless connection of lean processes with neither stock nor time buffers, manufacturers are unprotected against disturbances that destabilize the SC system [15]. Risk management can reduce the potential for disasters but it can neither prevent nor efficiently address smaller disruptions and deviations. In these cases companies need a supply chain event management (SCEM) system that identifies disturbances (i.e. events) early through a comprehensive real-time monitoring system (e.g. RFID-based) and suggests counter-measures. These reactions have an operational focus and try to uphold an efficient production despite impending knock-on effects of events. One large group of measures, besides e.g. the reintroduction of time and stock buffers, are adaptions of the production schedule and thus, the pearl chain sequence. However, rescheduling methods make assumptions that are often insufficiently aligned with real-world problems [19, 14, 13] and focus solely on production issues while neglecting the implications of today's tight integration of supply chain with production processes. Despite ample methods [16, 19, 17], planers still find it difficult to react to events and to hold the supply chain stable. Hence, this paper proposes and evaluates a rescheduling approach for a pearl chain sequence of a BTO assembly line that includes implications of event-prone JIS delivery processes.

## 2 Literature Review

The scheduling environment is divided into a static and dynamic environment [19, 16]. In the former, a finite set of orders has to be scheduled without the presence of uncertainty. This paper assumes a *dynamic and stochastic environment* in which an infinite set of orders is subject to uncertainty of some parameters. A scheduling problem of a manufacturer is specified further with the $\alpha \mid \beta \mid \gamma$ notation [13] that refer to the machine environment, processing characteristics and the scheduling objective.

Two of the more complex *machine environments* are job and flow shops that are characterized by the existence or lack of process flow variability, which is due to a multiple stage production process [13]. We model a MMAL and consequently a flow shop where every order has to be processed on the same sequential stages. Assumptions for *processing characteristics* of flow shops differ considerably from job shops and often exclude preemption (i.e. interruption of processing), recirculation, setup times, and machine breakdowns [17]. One important characteristic of flow shops is the availability and size of buffers (i.e. in-process inventories) between stations. A limited buffer implies blocking while a no-wait system like the tact-driven, constantly moving MMAL considered in this paper demands that orders cannot wait between stations and thus production start is delayed until processing is ensured [13]. The problem can be framed as a *proportionate flow shop problem* with equal processing times at each station and without intermittent buffers (MMAL does not halt). The *(re)-scheduling objective* aims either at operational (e.g. asset utilization) or market targets (on-time deliveries) [13]. For instance, makespan is the completion time of the last scheduled order. Its minimization implies a good utilization [13]. Other measures are often a variation of the earliness/tardiness criterion that are sometimes combined with the nervousness criterion to balance permutations [10].

In practice, scheduling is driven by uncertainty [11] while rescheduling is driven by the occurrence of a disturbance. Both concepts can be applied to different degrees in a dynamic and stochastic environment. Approaches with a focus that is entirely offline (i.e. robust scheduling) devise an initial schedule that is not updated while online approaches (i.e. totally reactive scheduling) make all processing decision locally in real-time. A representative for the latter is the choice of the most appropriate dispatching rule [7]. In a dynamic and stochastic environment, predictive-reactive scheduling is the only approach that combines scheduling and rescheduling [19, 16]. It follows a two-step approach where an initial schedule is devised (generation step) and then updated (control step). The interval of an update step is defined as periodic, event-driven, or a combination of both. Since the JIS deliveries to the assembly system are disrupted, a predictive-reactive (re)-scheduling with an event-driven policy is employed. A final aspect is the applied repair strategy that takes effect when a policy triggers a rescheduling. It is characterized by the degree to which it overhauls the initial schedule (partial or complete). This paper presents a partial repair strategy for event-prone JIS deliveries to BTO production systems.

## 3 Problem Formulation

Fig. 1 illustrates a tractor assembly line. From the virtual order bank (VOB), customer orders are sequenced on a weekly basis through a scheduling based on order priority. The scheduled sequence is one week long and fixes the production programme for week 5 – i.e. specific assembly times and the according delivery dates for JIS components. The preceding 4 weeks were scheduled earlier and constitute the frozen zone. It is a pearl chain of over 1200 customer-specific orders that will be assembled over 4 weeks. The length of the frozen zone is determined by the JIS supplier with the longest order to delivery (OTD) time. Around 10 components of the tractor (e.g. drive) are delivered JIS. For each component, a customer can choose between several versions. Thus, each JIS supplier has his own customer-specific sequence that runs in parallel to the order sequence of the manufacturer. They all converge on the assembly line.

From this use case, a model is developed that is generalizable for most BTO assembly systems with JIS deliveries (e.g. automotive industry). Customer orders for a single product arrive randomly in the VOB (see Fig. 1 and Fig. 2), modelled through the Poisson process with exponentially distributed arrival intervals $\lambda$. Customer orders are associated with an order time $o_j$ and a random committed due date $d_j$ that is bound on the lower end by the minimum OTD time of the supply network and its double on the upper end. These limits are largely in accordance with an empirical investigation at the case partner, where they were found to be 4 and 12 weeks respectively [8].

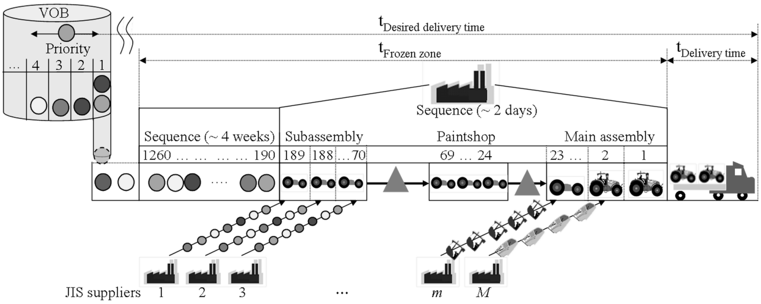

**Fig. 1.** Industrial case study

The SC consists of $M$ suppliers ($1 \le m \le M$) that each supplies one station at the MMAL with a component family that comprises $N$ products ($1 \le n \le N$) (Fig. 2). When ordering, a customer can select a specific component $n$ of each family to customize his product. The sum of components ordered by a customer constitutes his individual product configuration that is sourced JIS. Each supplier $m$ has a specific OTD time $\zeta_m$ that is subject to random variation due to disturbances. New orders that are not yet sequenced are part of the VOB (see Fig. 2) where orders are sorted by due date $d_j$ from latest to earliest. A one week production schedule is devised weekly with component orders being sent to the suppliers. Within the scheduled sequence of $J$ customer orders ($1 \le j \le J$), each order $j$ is associated with a fixed assembly sequence position $s_j$ and thus, a release date $r_j$ when final assembly is scheduled to start.

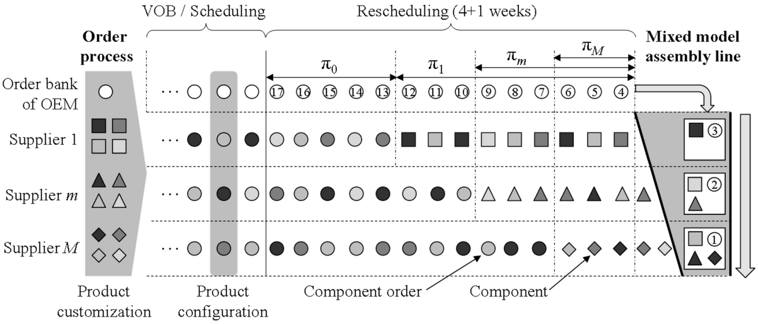

**Fig. 2.** MMAL model with JIS component deliveries

The newly scheduled component orders then successively enter the frozen zones of the $M$ suppliers, depending on $r_j$ and the supplier-specific lead time $\zeta_m$ (see Fig. 2). Once an order enters the frozen zone of supplier $m$, the production of component $n_{mj}$ has begun. Due to this supply chain setup, the mixed model assembly line (MMAL) assembles a total of $n^m$ product variants. Using the $\alpha \mid \beta \mid \gamma$ notation a $Fm \mid p_{mj}=p_j \mid \sum T_j / J$ production system is modelled. It is a *proportionate flow shop problem* (PFSP) with $m$ work stations in series; the processing times $p_{mj}$ of order $j$ on station $m$ are identical and equal to $p_j$; the objective function is to minimize the average order-related delivery delay. We assume the MMAL to be a black box where processing times are deterministic and known. A resequencing within the MMAL is excluded (i.e. no mixed-bank buffers [12]). Orders that cannot be assembled due to missing components are moved to the rework area. Completed orders are shipped to the customer and the order-specific tardiness is recorded (if completion time $c_j > d_j$).

# 4 The Multiple Permutable Subsequences Concept

Although providing planning stability, a long frozen zone of e.g. 4 weeks leads to an increase of the probability that disturbances affect supplier sequences. The mismatch between real and planned state of ordered components results in delayed or failed deliveries [4]. Because components are customer-specific, in either case the current sequence position $s_j$ of an order $j$ cannot be hold. Fig. 3 illustrates removal strategies.

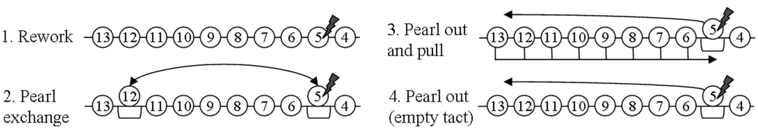

**Fig. 3.** Removal strategies for affected customer orders

The case partner currently moves affected orders to the end of the sequence and advances all others (third strategy in Fig. 3), which has several implications. First, schedule changes have to be communicated to all JIS suppliers, who in turn have to provide the components of advanced orders faster than their frozen zone, which is not always possible and compromises product quality (rush jobs). In urgent cases, emergency transports are devised. Second, the rescheduling policy avoids an empty tact but decreases pearl chain stability since the removal of one order alters the position of the others. This leads to suboptimal due date adherence and confusion on the shop floor. The latter refers to difficulties in aligning the material flow of the right components with the correct machines. Third, high instability with missing or wrong material coupled with a continuously moving assembly line results in rework. While assembly takes a few days, rework can take weeks, further jeopardizing due dates.

To avoid these drawbacks, it is assumed that customer orders are only moved back in the sequence. Thus, strategies two and three in Fig. 3 are invalidated and only ‘rework’ and ‘empty tact’ remain. The rework strategy reflects today’s supply networks that lack real-time monitoring systems. Components that are delayed or failed are only noticed at the OEM when assembly and component sequences cannot be aligned. The unfinished product then moves to the rework area after assembly. Through a continuously monitored supply chain costly rework is avoided because orders can be removed from the sequence when components are affected by an event. This approach, however, poses the question where the removed order is reinserted into the sequence. To this end, we propose the *multiple permutable subsequences* approach that is based on the insight that the frozen zone is divided into several component sequences that differ in length due to individual OTD times of JIS suppliers (Fig. 4).

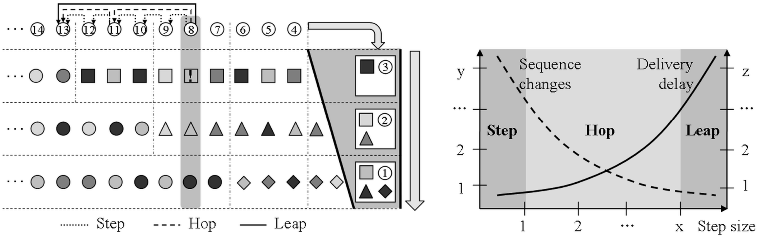

**Fig. 4.** Trade-off between schedule optimality and nervousness during rescheduling

Fig. 2 and Fig. 4 (starting with $s_j = 13$) show that within the *totally permutable subsequence* (TPS) $\pi_0$ orders are easily rescheduled because components are not in production. Hence, the TPS is reduced whenever an order enters the frozen zone of the supplier with the longest OTD, marking the beginning of the *partially permutable subsequences* (PPS) $\pi_m$. Thus, while one component is affected by an event, other components that are already in production would still be delivered on time, which a rescheduling strategy needs to consider. Fig. 4 shows three strategies based on the individual order step size for reinserting an order when it is in the PPS: *step*, *hop* and *leap*. The step strategy moves every order, starting with the delayed order, one sequence position back, resulting in high nervousness but low cumulated delivery delay. In contrast, the hop strategy removes orders based on a criterion (e.g., due date) to balance indicators. Lastly, the leap strategy removes an order from its current position and moves it to the back of the affected component sequence (e.g., from $s_j = 8$ to $s_j = 13$ in Fig. 4). All order sequence positions behind the reinserted order are then increased by one. The resulting empty position (e.g., $s_j = 8$ in Fig. 4) can be filled if another order further down in the sequence is delayed or failed.

## 5 Evaluation

The model with the rework and leap strategies was implemented into Plant Simulation from Siemens PLM Software. The MMAL is supplied by 3 JIS suppliers (drive, engine, and cabin) with a respective lead time of 18, 12, and 6 days and an on-time delivery reliability of 86, 91 and 97% respectively. Each supplier offers 4 different component versions that are randomly chosen by the customer, whose orders arrive according to the Poisson process in mean intervals of 30 minutes. The MMAL assembles 64 different variants and runs at a tact time of 30 minutes. If during assembly customer-specific components are missing, the order is moved to the rework area. The simulation ran for 100 days, including a calibration phase of around 30 days.

Fig. 5 compares the performance of the rework and leap strategies. As outlined earlier, the foremost objective is to have products that do not require rework after assembly. The leap strategy fulfils this requirement by increasing the assembly volume by 23.6% (i.e. products that do not need rework) while virtually eliminating rework that is due to missing components. Through the delay of the product assembly for orders where components are missing, however, the overall production volume is decreased by 3.2% over the simulation time. Furthermore, a total of 765 sequence positions remained empty due to the order removal, which reduces the utilization of the assembly line. The comparison between rework and leap for this indicator is misleading, however, because work stations that lack the correct component are also idle when the rework strategy is applied. Thus, the difference in utilization between the two strategies is less than Fig. 5 suggests. The final indicator is the number of sequence positions that were filled through the application of the leap strategy. These 270 positions became empty through a problem in the supply chain for an order but were filled at a later point in time through the inserting of another order further downstream. As predicted in Fig. 4 and shown in Fig. 5, the leap strategy is associated with a poor performance in regard to the average product delivery delay. It rises from about 4 hours for the rework strategy to more than 20 hours when the leap strategy is applied.

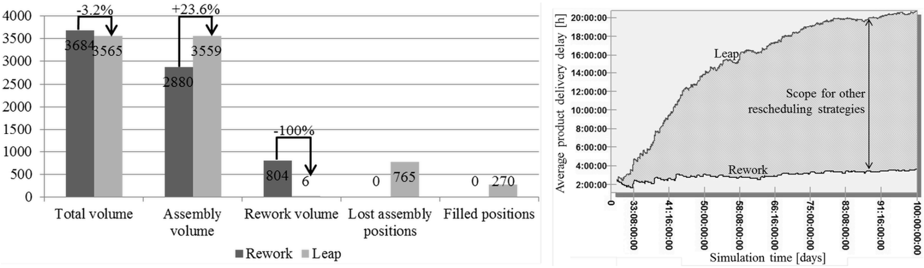

**Fig. 5.** Comparison of the rework and leap strategies

## 6 Summary

Modern BTO production systems are characterized by low inventories for main components that are sourced JIS. The respective component sequences merge seamlessly on the assembly line into a customer-specific product. Trends like global sourcing and lean management, however, have virtually eliminated the scope for variation in the supply processes. Thus, small and large events alike cripple the synchronization of the individual component sequences. A SCEM system identifies these disturbances early through a comprehensive real-time monitoring system and suggests counter-measures. To repair the affected production sequence, this paper presents the multiple permutable subsequences concept that divides the frozen zone into several subsequences of diminishing rescheduling flexibility. The evaluation for one strategy (‘leap’) showed that through the early removal of affected customer orders from the sequence costly rework due to missing JIS components is avoided. Since the strategy moves an order to the end of the partially permutable subsequence, however, the average product delivery delay is worse when compared to the status quo. Thus, future work focuses on the implementation and evaluation of other strategies that increase performance.

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