Advanced Supply Chain Information for Rule-Based Sequence Adaptations on a Mixed-Model Assembly Line with Unreliable Just-In-Sequence Deliveries

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Abstract: The proliferation of just-in-sequence (JIS) deliveries has raised the vulnerability of assemblies to costly production stoppages or rework due to missing components. Through a comprehensive real-time supply chain monitoring systems, these supply issues can be detected early and affected orders removed from planned assembly sequences in time to avoid production disturbances. Using simulation analysis, this paper explores the impact of unreliable JIS deliveries and the mitigation potential of transparent supply chains that allow a rule-based order resequencing on a mixed-model assembly line. The results indicate that (i) rework due to unreliable JIS deliveries can be eliminated and (ii) the trade-off between schedule nervousness and optimality can be balanced, making the proposed rule a feasible approach.

Keywords: Production systems, Discrete event systems, Model-based control, Production control, Simulation analysis, Supply chain event management, Enterprise networks, Resequencing

1. INTRODUCTION

For years, manufacturing companies in general and automakers in specific focused on combining the benefits of mass production and product variety to win customer orders by providing them with exactly their desired product configuration (Ro et al., 2007). An increase in customization options was largely achieved by outsourcing customer-specific modules to fewer but more closely integrated suppliers. Today, product variety has proliferated substantially. For instance, of a BMW 7 series car there are \(10^{32}\) possible configurations (Hüttmeir et al., 2009). To still ensure economic and efficient mass production processes with a lot size of one, companies are not only forced to switch seamlessly between variants of the same model but also different models on the same production lines through common platforms (Holweg and Pil, 2004). For example, through the common VW MQB platform all variants of certain models (VW Golf, Audi A3, Skoda Octavia and SEAT Leon) are built from the same set of basic components and can be assembled on the same production lines, offering ‘a fabulous variety of brands and styles while slashing manufacturing costs’ (The Economist, July 7th). For many of the remaining customer-specific components and modules that are marked by high variety, value and size, OEMs have adopted just-in-sequence (JIS) delivery strategies to further reduce space requirements, inventory and handling costs (Thun et al., 2007). In contrast to just-in-time, strategies that employ JIS not only deliver parts in the right time, quality and quantity but moreover synchronize the production of supplier and buyer to enable a sequenced part delivery (Wagner and Silveira-Camargos, 2012). A survey of car plants located in Germany that covered 80% of the annual German production volume (i.e., around 4 million cars) found that on average 17 modules – or 40% of a car’s parts volumes – are delivered JIS with a continuous upward trend (Wagner and Silveira-Camargos, 2012). One premium automaker sourced 35 parts of one model JIS. The ratio of JIS modules to JIS suppliers for specific car models is reported to be close to a 1:1 relationship. This trend towards zero time and stock buffers, however, is not confined to automakers. Another study reports that a maker of agricultural machinery sources around 10 parts JIS for its tractors (Heinecke et al., 2012).

In contrast to stock-based supply strategies, the tight coupling of supplier and buyer in a JIS relationship raises the vulnerability of assembly processes to supply disturbances (Ivanov et al., 2012). This vulnerability is further aggravated by continuing cost pressures that foster the global dispersion of supply chains to low-cost regions so that also long-distance relations are commonly employed in JIS scenarios (Wagner and Silveira-Camargos, 2012). At the same time, studies show that quality problems and delivery delays are seen as the most common supply-side problems (Wagner and Silveira-Camargos, 2012, Thun and Hoenig, 2011). In contrast to large scale catastrophes (e.g., earthquakes), these minor occurrences (‘events’) cannot be efficiently and economically addressed through preventive risk management. Rather, a comprehensive real-time supply chain monitoring system (e.g., RFID-based) enables the early detection of problems with individual components through a supply chain event management (SCEM) system before it reaches a company (Dias et al., 2009). This requires close integration
of information flows between supplier and buyer through common communication technologies, marking a step from individual plant and logistics control to inter-enterprise collaboration (Nof et al., 2006). A SCEM system is then empowered to address events that compromise the current sequence position of ordered jobs through a timely and appropriate reaction (Liu et al., 2007). Besides employing costly emergency logistics, the early problem identification allows order rescheduling. It focuses on the order removal and its criterion-based reinsertion in the planned sequence. Since production sequences are planned days or weeks ahead, the reinsertion requires the removal of the order that occupies the chosen position, triggering a series of sequence alterations (Heinecke et al., 2012). Thus, the questions in rescheduling are i) where to reinsert the affected order and ii) the degree to which the sequence is overhauled to restore optimality.

This paper first illustrates the need for reactive measures through a SCEM system by exploring the impact of unreliable JIS deliveries to a mixed-model assembly line (MMAL). To this end, the stability of the individual, transparent component supply chains is varied in a simulation analysis. Next, the paper examines the mitigation potential of a transparent supply chain in conjunction with a SCEM system. Through the application of different rule-based order rescheduling strategies, the simulation analysis illustrates that the worst effects can be mitigated at the expense of a trade-off between sequence nervousness and optimality. The paper is structured as follows: Section 2 places the paper within the context of the MMAL rescheduling literature. Section 3 then formulates a MMAL model with unreliable but monitored JIS deliveries and delineates rescheduling strategies. Section 4 introduces the simulation parameters and presents the evaluation. Section 5 concludes the paper with a brief summary and outlook.

2. RELATED WORK

The problem of rescheduling JIS deliveries to a MMAL is rooted in literature with the predictive-reactive scheduling problem in a flow shop environment (Pinedo, 2008). The assumed flow shop is characterized by no buffers, equal and deterministic station processing times, connection of stations by a paced conveyor, placement of jobs in the same intervals, and closed stations. Predictive-reactive scheduling then employs a two-step process whereby an initial production schedule is devised and updated either periodically or when events occur (Proth, 2007). Since events cause a deterioration in performance and consequently trigger a rescheduling, they are also called rescheduling factors (Vieira et al., 2003). A recent paper observed that the factors considered by the great majority of the current literature are principally machine breakdowns and new job arrivals (Katragjini et al., 2012). With company-internal and demand-side risks, however, this covers only two of the three main risk sources that can cause a rescheduling (Wagner and Silveira-Camargos, 2012).

In literature, supply-side rescheduling factors – the focus of this paper – are either mentioned as a delay in the arrival (or shortage) of materials (Vieira et al., 2003) or the variation in job ready or release times (Pinedo, 2008). The latter denotes the earliest time all prerequisites for a job are fulfilled and processing can start. In a flow shop environment with JIS deliveries these factors cause blocking that prevents an order \( j \) from leaving station \( m \) due to missing material (Pinedo, 2008). Thus, preceding orders and stations are temporarily blocked. In this scenario various reactions are possible (Boysen et al., 2009b): (i) line stoppage until material arrives and flow can resume; (ii) utility workers support stations after resequencing of orders to avoid overload; (iii) unfinished tasks and all successors are left out and executed off-line. Although supply side problems occur frequently (Blackhurst et al., 2005), there is a lack of published rescheduling approaches that explicitly deal with supply-side events in general and JIS-related problems in particular (Boysen et al., 2009a). One explanation is that companies lack real-time supply chain status information, which prohibits an order rescheduling before constraints limit available reactions. Another explanation is that it is difficult to align idealised rescheduling models with real-world problems that are marked by constraints (Portugal and Robb, 2000, Boysen et al., 2009a, Pinedo, 2008). These range from usual workload limitations (e.g., only every 4th car has a sunroof) to a JIS environment where sudden sequence alterations are risky because the whole supply base must respond simultaneously (Wagner and Silveira-Camargos, 2012).

A recent paper integrated these two constraints in a mixed-integer linear program (Gujjula and Gunther, 2009). To avoid a line stoppage due to missing JIS parts, the affected workpiece is first removed from the sequence. With the objective of minimizing utility workers and order postponement costs, reinsertion was then limited to a certain sequence range from its former position. The results indicate that performance in required utility work (i) improves when rescheduling is employed and (ii) depends on the employed reinsertion range. Through the application of set-aside bins and restacking services this approach belongs to the group of physical rescheduling that requires buffers or sorting machines along the assembly line or between successive departments (Boysen et al., 2009a). A few academic papers consequently discuss the resulting sorting strategies and buffer layouts that allow automakers to execute short-term sequence adjustments in a JIS environment (Ding and Sun, 2004, Meissner, 2010). Specifically in regard to disruptions of flow shops, another recent paper extends the existing rescheduling literature in two important aspects through the employment of (i) a bi-objective function and (ii) random simultaneous schedule disruptions (Katragjini et al., 2012). The bi-objective function considers efficiency measured through the schedule makespan and instability through the number of tasks with altered starting times. The study further considered three different events that disrupt the predictive schedule. Employing various disruption recovery routines, it was found that the Iterated Greedy algorithm generally outperformed all other routines for the bi-objective function and should be employed when time is not of concern. If fast execution times are required, the local search method is suitable. The physical rescheduling with buffers, however, is restricted in praxis due to limited space – especially along assembly lines – that only allows for a few key buffers (e.g., between body and paint shops). Also, in the automotive
assembly it is common practice to further process incomplete workpieces and subsequently send them to an off-line repair station rather than resequencing them (Boysen et al., 2009a) – the same was found for agricultural machinery (Heinecke et al., 2012). Thus, it is reported that ‘up to half of the productive staff is employed in off-line repair areas at major German car manufacturers’ (Boysen et al., 2009a).

Besides buffers, another group of reactions that received comparatively little attention is virtual resequencing that changes the assignment between workpiece and order (Boysen et al., 2009a, Boysen et al., 2012). The logic is that product variants are specified successively through the installation of features during assembly. Thus, the assignment of an order that requires a disrupted machine can be swapped with one that does not. For instance, considering a complete automotive assembly system it was found that virtual resequencing can outperform its physical counterpart – albeit for low product variety – when identifying swap models prior, past, as well as prior and past the paint shop (Fournier and Agard, 2007). In a JIS environment, however, this approach is of limited use because part flows from the entire supply base are fixed in the short-term. Consequently, the exchange can only occur in the rare case when two orders merely differ in the affected part (e.g., same color car body). All successive components are fixed and have to match the customer specification of the swapped order.

Building on the aforementioned works, this paper also employs a bi-objective approach of optimality in conjunction with nervousness and incorporates the implications of multiple possible supply disruptions. It extends the existing literature in a number of ways. First, it assumes monitored JIS supply processes that provide advanced information about the feasibility of the predictive MMAL schedule. Thus, missing material is not noticed in the receiving department but at specific points along the supply chain. This enables a virtual resequencing of orders without the necessity of reassigning workpieces on the assembly line. Thus, this paper aims at production sequence control using real-time status data from the supply chain. Second, it explicitly incorporates JIS implications where suppliers synchronize their production with the OEMs schedule. Hence, their highly-individual, customer-specific part sequences are fixed for days ahead of assembly. Thus, unconditional sequence changes are only feasible as long as suppliers have not commenced production – changes afterwards lead to a build-up in stock until the order is assembled. Third, the developed model is based on an industry case study, considering a realistic JIS scenario: A make-to-order supply chain with an OEM that employs a single-sourcing strategy for each JIS part.

3. MODEL FORMULATION

The model is based on a supply-assembly model (Xiaobo et al., 2007) that was adapted and enhanced for a recently published case study of a tractor assembly (Heinecke et al., 2012). As shown in Fig. 1, during the order process customers choose their individual configurations from various options and specify a due date \( d_j \). The virtual order bank (VOB) contains all unscheduled customer orders from which are then sequenced on a weekly basis to fix the production program of week 5. Scheduling is based on priority, which is determined by the closest due dates. The preceding 4 weeks were scheduled earlier and constitute the frozen zone, which provides planning stability for suppliers. 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 roughly determined by the JIS supplier with the longest order-to-delivery (OTD) time – about 18 days in the case study. All of the sequenced orders \( J (1 \leq j \leq J) \) are associated with a fixed sequence position \( s_j \) and release date \( r_j \) when final assembly is scheduled to start. Around 10 components of the tractor (e.g., engine) are delivered JIS from \( M \) suppliers \( (1 \leq m \leq M) \) with none constituting an optional feature. Each supplier delivers a component family with \( N \) products \( (1 \leq n \leq N) \) from which a customer chooses a specific version \( n \). Consequently, the mixed-model assembly line (MMAL) produces a total of \( n^M \) possible configurations.

The sum of components ordered by a customer constitutes the individual product configuration that is sourced JIS (Fig. 1). Dependent on the individual delivery time \( \zeta_m \) of component \( n_{mj} \) there exist three distinct cases of how the \( M \) customer-specific sequences merge on the MMAL: (i) Component and order are ready so that order proceeds as planned; (ii) Component is ready before the customer order is scheduled at the respective station, resulting in its temporary storage; (iii) Order is delayed but order is scheduled to be processed. In accordance with industry practice (Boysen et al., 2009a), it is assumed for the last case that processing continues and that the incomplete workpiece is subsequently send to a rework area. It is assumed that the lack of one component does not compromise the assembly of another. Completed orders are immediately shipped to the customer. Since a JIS setup is modelled, the production processes of supplier and buyer are insofar synchronized that production of \( n_{mj} \) at the supplier is only triggered when the distance to \( r_j \) is the supplier-individual OTD_{mc}. Due to stochastic influences, JIS deliveries are unreliable to a small percentage, so that the delivery time \( \zeta_m \) of component \( n_{mj} \) can take a random nonnegative real value that is larger than the OTD_{mc}. Thus, component status and the sequence position of the customer order can get out of sync, making its current assembly schedule obsolete. In order to avoid rework due to delivery delays, a rescheduling model is proposed. To this end, the model is enhanced with real-time component monitoring capabilities (see Fig. 2) that allow...
feedback when JIS supply processes fail to bring the right product, at the right time, to the right place, in the right quality and quantity. Supply-side problems have a temporal dimension and are noticed at monitoring points through a delayed or missing reading of a component that ultimately materializes at the OEM through a delivery delay or delivery failure – the latter implying that components are of the wrong quantity or quality. As illustrated in Fig. 2, given that a SCEM system finds that actual JIS component status $s_{nj}$ and planned assembly sequence position $s_j$ of the customer order $j$ are out of sync, a rescheduling is triggered.

During rescheduling the affected order is first removed from the planned sequence. The model assumes that it can then only be postponed because otherwise the whole supply base must provide components that are already in production faster than originally planned, which compromises quality. The subsequent steps then aim at reinserting the order into the existing sequence and are based on the multiple permutable subsequences concept (Heinecke et al., 2012). It builds on the insight that JIS suppliers require different OTD times and thus, trigger component production for the same customer order at different times. Due to the asynchronous component production starts the approach divides the order sequence into parts of decreasing rescheduling flexibility. They go from the totally permutable subsequence $\pi_0$ (TPS) where a rescheduling is totally flexible to the partially permutable subsequences (PPS) where some to all components of an order are fixed and in production (compare Fig. 1). For instance, Fig. 2 shows that an early event at supplier 1 can be communicated to the other suppliers that have not started production on the affected customer order to adapt their sequence. To include the implications of the multiple permutable subsequences approach with the individual status of the various JIS components, a rule-based rescheduling model is proposed. It is based on the order step size when choosing a position for reinserting an order. As shown in Fig. 3, the leap strategy maximizes the distance of the affected order from its former position by moving it to the sequence position that marks the end of the PPS that contains the affected JIS component. For a delayed component this guarantees enough time to be ready before the order is scheduled for assembly again while a failed component can be reproduced. Other components that are in production and required by the resequenced order are temporarily stocked after completion while the production start of component orders is delayed. Conversely, the step strategy aims at reinserting an order as close as possible to its former position. Given that a component is delayed the range has a lower bound of the quantified delivery delay (e.g., 3 positions in Fig. 3) while for a failed component it is the respective OTD time of the supplier. If necessary, however, these bounds can be avoided through a component swap where the strategy looks for the next order in the sequence that requires the same component version and swaps their order assignments.

Fig. 2. Predictive-reactive scheduling in monitored networks.

Rescheduling an order has two consequences (see Fig. 3): (i) its reinsertion into the sequence requires the displacement of another order and (ii) its removal leaves an empty sequence position. The former is addressed by increasing the sequence position for all orders following the reinsertion that are already part of a PPS until one order is moved into the TPS. The empty position is filled in case another order further down in the sequence is affected by an event and thus triggers another rescheduling. Performance is measured through several indicators. First, the okay-rate measures the number of workpieces that leave assembly completed. Second, the average delivery delay per workpiece measures optimality. Third, the average reschedules per workpiece measures nervousness. Literature reports that there exists a trade-off between schedule optimality and stability (Heinecke et al., 2012). Since the step and leap strategies represent to opposed extremes, the former results in good due date adherence but high schedule nervousness while it is vice versa for the latter. To this end the dynamic strategy decides on the grounds of the due date which strategy is employed:

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IF Current.Time + Leap.Completion.Time > Order.DueDate
THEN use step strategy
ELSE use leap strategy
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4. SIMULATION AND EVALUATION

For the evaluation, the model with the respective strategies was implemented into the discrete event simulation tool Plant Simulation from Siemens PLM Software. The MMAL is supplied by three JIS suppliers (drive, engine, and cabin) with a respective lead time of 18, 12, and 6 days. Each supplier offers 4 versions that are randomly chosen following a uniform distribution by the customer. Their orders arrive according to the Poisson process in mean intervals of 30 minutes. The order due date is uniformly distributed and bound between the minimum system OTD time (i.e., rush job) and it’s double on the upper bound. The MMAL
assembles 64 different product variants and runs at a tact time of 30 minutes. If during assembly components are missing, the order is moved to the rework area. The simulation ran for 100 days, including a simulation calibration phase of 30 days. The delivery reliability of the individual JIS supply chains was varied in steps of 2% from 99% to 93%. The remaining percentage share for the probability of an event was divided between 10% for a failed component and 90% for a delayed one. The length of the delay is modelled using an exponential distribution with bounds in the range $Ex[2,\ldots,48h]$.

Workpieces (i.e., chassis) onto which the JIS components are mounted are sourced without delay from the buffer between paint and assembly and provided in the scheduled sequence. Fig. 4 shows the impact of increasingly unreliable JIS supply. As expected from reliability theory and serial systems, a 2% drop in the reliability of the three supply chains results in a disproportional drop of 4% in the assembly okay-rate. For 93%-reliable supply chains, the okay-rate drops to only 81%. Missing components then frequently inhibit the assembly of the order and result in a proportional increase in the rework load. Given that on average 17 parts are sourced JIS from 17 different suppliers in the German automotive industry, the respective supply chains have to be highly reliable to avoid rework and delivery delays due to missing components.

The dynamic strategy addresses this trade-off while still avoiding rework due to missing components. The comparison of Fig. 5 and 6 reveals that it results in a more balanced performance. For 97%-reliable supply chains the dynamic strategy results in an average delay of below two hours (Fig. 6), attaining the same level as the step strategy (Fig. 5). At the same time it results in only 15 reschedules per job (Fig. 6), attaining a rescheduling frequency that is slightly above ‘leap’ but well below ‘step’ (Fig. 5). Considering the delivery delay, Fig. 6 shows that the strategy performs well across reliability settings, remaining below 3 hours throughout the simulations. For the rescheduling frequency, however, performance decreases disproportionally. The results indicate that the rule is applicable for reliable supply chains but results in high schedule instability for event-prone ones.

The proposed rescheduling strategies virtually eliminate this rework. Fig. 5 shows for 97%-reliable JIS supply, however, that a trade-off between optimality and stability exists. While ‘leap’ results in minimal reschedules per job (grey line) but high delivery delays (black line), the opposite is true for ‘step’. Thus, in industry the former results in poor customer satisfaction while the latter will inevitably incur error costs due to frequent schedule overhauls. Fig. 5 underlines that neither strategy represents a feasible option in praxis.

5. CONCLUSIONS

Modern assembly systems are marked by just-in-sequence component deliveries. Trends like global sourcing and lean management, however, have virtually eliminated the scope for variation in these processes. Thus, small and large events alike cripple the synchronized merging of the various sequences that result in costly line stoppages and/or rework. The paper illustrates through a supply-assembly model that tightly integrated supplier-buyer relationships with unreliable processes cause a disproportionate increase in rework. The model is then enhanced with monitoring capabilities that allows a supply chain event management (SCEM) system to identify an event early and enact reactions. Accordingly, the paper presents rule-based resequencing strategies that build on the multiple permutable subsequences concept (Heinecke et al., 2012). It restricts the unconditional resequencing of orders when customer-specific components go into production at the supplier. The evaluation shows that neither minimizing nor maximizing the distance to the former position of an order is a feasible strategy in industry when
employing the bi-criteria approach of schedule nervousness and optimality. Thus, the paper introduces a dynamic strategy that assigns an approach based on the order due date. It finds that performance improves, making it a feasible strategy for robust supply chains. When these become increasingly unreliable, however, performance in regard to nervousness is intolerable. The issue can be resolved by skewing the sensitivity of the dynamic rule towards the maximization of the distance. In future, the model will be enhanced with a criterion-based strategy that varies the distance to the former sequence position. Furthermore, industry representatives proposed to include planning with slack by leaving intentional sequence gaps during scheduling.

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