Simulation-based Sequencing Algorithm for MRO Operations of Train Couplings

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Abstract. Sequencing rules are often used in production control to improve key performance indicators, such as cycle time, mean tardiness and on-time delivery. However, for Maintenance, Repair and Overhaul (MRO) processes, there is a development need for sequencing rules, which effectively improve these indicators since specific requirements have to be considered and recent studies have mainly been using standard rules and do not allow a clear conclusion. This paper describes the modeling and validation of a real-case scenario, the MRO of train couplings by means of an event-driven simulation. The simulation model is used in order to derive and test a new sequencing rule, the Fix-and-continue algorithm (FACA), as well as to compare its results with standard sequencing rules concerning average cycle time, mean tardiness and on-time delivery. Thereby, the potential of the algorithm is revealed.

Introduction

Due to the rising level of complexity and value of machines, systems and products, especially in the field of transportation and energy, their Maintenance, Repair and Overhaul (MRO) are becoming increasingly important [1]. A survey, conducted in 2011, showed that for 62 \% of German MRO polled companies define the reliability of their services as their main goal [1]. This fact stresses the importance of a high service performance, which means combining high product quality with short cycle times and high delivery reliability. The majority of MRO companies is organized as job shop production with branched material flow since they have to handle a wide range of products and a high rate of variants [2]. Thus, tracking and controlling the material flow in production is clearly impeded. This leads to missing materials and consequently to waiting queues in front of the shop floor’s machining centers. The unknown condition of products’ individual components before their disassembly and inspection in the maintenance site increases the problem and causes stochastic work plans and uncertain processing times [3]. Extended and fluctuating cycle times are the consequence. In order to meet these challenges at MRO, an adequate production planning and control should be realized [4]. The majority of studies and approaches in the field of MRO, however, focuses on improving manufacturing technologies whereas the improvement of production control in particular has not received the same attention [2]. Thus, in association with a software manufacturer and a MRO company, the Institute of Production Engineering and Machine Tools (IFW) developed the innovative manufacturing execution system CELERITAS. This system is characterized by agent-based software architecture, which means that it has the ability to resolve complex tasks autonomously, and utilizes specific algorithms for the production control of MRO companies, such as sequencing rules [5]. The sequencing algorithms were derived and tested by means of an event-driven simulation from a real-case scenario, the MRO of train couplings.

Event-driven simulations are discrete and manage events in time. This means that each event occurs at a particular point in time and marks a change of state in the system [6]. Thereby, complex issues, such as the performance of production systems, logistic processes and the material flow, can be simulated. In particular, they enable to analyze the process chain without intervening in the real production process.
This paper describes, at first, the state of knowledge concerning the simulation of sequencing rules for MRO processes. Furthermore, the modeling and validation of the real-case MRO scenario of train couplings by means of the event-driven simulation is described. In conclusion, the derivation of a new sequencing algorithm and its results in comparison to standard sequencing rules concerning average cycle time, mean tardiness and on-time delivery are shown.

State of Knowledge

Sequencing Rules in MRO. In order to cope with the challenges of production control arising from the MRO specific characteristics, different approaches propose the use of sequencing rules, which are also known as scheduling rules and dispatching rules. For example, it has appeared from various examinations that beside the unknown condition of products due to the job shop production, long waiting times exert a strong influence on the products’ cycle time [2]. Sequencing rules provide a possibility to reduce these waiting times. They are used to determine the priority of each job or component in production, whereas jobs or components with the highest priority at work stations’ queues are processed first [7]. In [8] a distinction is made between priority rules and scheduling rules. Priority rules assign a scalar value to each waiting job or component. These values determine the sequence of jobs. Scheduling rules specify which waiting job or component is to be scheduled in preference to the others. Following [8] priority rules comprise a subset of scheduling rules, since scheduling rules may contain one or more approaches in addition to or instead of a priority rule. Sequencing has been subject to little research to date in the field of MRO [9]. [10] introduces more than 90 different rules, however, five well-known sequencing rules have been mainly tested at MRO simulations and are set out in Table 1.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Full Rule Name</th>
<th>Description</th>
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<tbody>
<tr>
<td>FIFO</td>
<td>First-In, First-Out</td>
<td>The job or component which arrives first at the work station is processed first.</td>
</tr>
<tr>
<td>SPT</td>
<td>Shortest Processing Time</td>
<td>The job or component with the shortest operation processing time is processed first.</td>
</tr>
<tr>
<td>LPT</td>
<td>Longest Processing Time</td>
<td>The job or component with the longest operation processing time is processed first.</td>
</tr>
<tr>
<td>EDD</td>
<td>Earliest Due Date</td>
<td>The job or component with the earliest due date is processed first.</td>
</tr>
<tr>
<td>JST</td>
<td>Job Slack Time</td>
<td>The job or component with minimum slack is processed first.</td>
</tr>
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</table>

[2] investigate the impact of FIFO, EDD and JST on aircraft engine maintenance by means of an event-d simulation in order to derive suitable sequencing methods. The outcomes of the simulation are analyzed by a variance analysis. The best results regarding cycle time and on-time delivery are achieved by the combination of FIFO/JST. [11] simulate scheduling rules to minimize flowtime and root mean square tardiness considering different levels of utilization. They find out that product complexity and capacity utilization of machinery have strong influences on the impact of sequencing rules in MRO processes. SPT leads to the best results regarding the improvement of average cycle time, whereas EDD is most effective in reducing mean tardiness. In further publications, sequencing rules for job-shop productions are simulated. [12] test different combinations of rules (FIFO, EDD, SPT, and JST) in an assembly shop with two subassemblies and one final assembly in terms of average cycle time and mean tardiness. The results show that combined rules do not perform well and suggest JST as the best rule regarding service performance. [13] simulate and compare five rules (including FIFO and SPT) at a flexible job shop with dynamic events, such as stochastic job arrivals and uncertain processing times, with a multi-agent system (MAS). The MAS uses a pheromone-based approach for coordination among the agents and provides the best outcomes. The last three studies above do not test their sequencing rules in real-case scenarios but in internally generated scenarios. Specific sequencing rules for the optimization...
of MRO productions with job shop have not been developed and simulated. [5] describes the need for further examinations, particularly in MRO companies. Summing up, a development need for sequencing rules, which effectively improve average cycle time, mean tardiness and on-time delivery, is created since recent studies have mainly been using standard rules and do not allow a clear conclusion. A new sequencing rule has to be developed, simulated and tested in a real-case MRO scenario in order to ensure its suitability for practical applications. Thus, the simulation software Tecnomatix Plant Simulation is used by the author to generate valid simulation models and to develop, analyze and verify effective sequencing rules for MRO companies.

Simulation-based Sequencing Algorithm for MRO Operations

Modeling the MRO of Train Couplings. MRO processes for complex products consist of five main parts in general, which have to be met in a certain order [2]. At first, the disassembly and inspection of the products take part. Both processes are executed in order to determine the individual components’ condition. The results are used as input data for the production planning and control (e.g. to create work plans or to allocate jobs to machines). Afterwards, the repair process (regeneration) is executed and represents the third main part. In conclusion, reassembly and quality check complete the MRO process. In view of the above, a suitable application scenario, the MRO of train couplings, was identified. At several maintenance sites, more than 80 different types of couplings, consisting of 60 up to 400 individual parts, are maintained by the MRO company in small batch series. The necessary repair workload in particular is not known until the components are disassembled and checked for defects.

As a simulation of 80 complex couplings requires an inappropriately high input of resources and leads to long simulation times, three representative coupling types were selected to be modeled, from which two are dealt with in this article for simplification (see Table 2). The couplings have different characteristics, such as the annual work load, the amount of individual components and the level of MRO complexity (e.g. couplings with or without a heating unit, amount and type of work steps, defect probabilities) in order to have as representative a cross-section of the product range.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Amount of individual components</th>
<th>Annual MRO work load [amount of couplings]</th>
<th>Level of MRO complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>55</td>
<td>200-250</td>
<td>medium</td>
</tr>
<tr>
<td>Type 2</td>
<td>405</td>
<td>15-25</td>
<td>high</td>
</tr>
</tbody>
</table>

Based on these facts, a simulation model of the MRO scenario was derived according to [6]. The focus was laid on the consistency of the data collected and the validity of the simulation model. Thereby, the following data were collected and implemented: material flow, transport times, processing times, manufacturing capacities, shift scheme, break scheme, machine availabilities, work plans, production orders and defect probabilities.

Regarding the validation of the simulation model, separate parts were checked isolated for validity using real production data from the MRO company. For this purpose, the production program from 2011 and 2012 was implemented in the simulation model. Considering that only a few coupling types were modeled, parameters such as utilization and work load at the simulation model would not reflect reality to a sufficient degree. Thus, functions (normal distributions) and machine parameter were derived from the collected data and implemented in the simulation model to adequately match the real situation. By doing so, valid simulation results for the investigated coupling types should be ensured. This fact has to be considered in the conclusion since, in particular, machine utilization and waiting queues in the simulation could be smaller than in the real process.

In order to obtain statistically reliable results, 20 simulations were run and analyzed (R = 20). Conclusively, the entire simulation model was validated by a comparison of the simulation results,
such as cycle times, with real production data. The couplings’ annual work load amounts are of high relevance for the validation since large numbers of couplings prevent misinterpretations due to stochastic effects. This can be shown with an example of probability of defect which has an influence on the fluctuation of average cycle time. The expected values were derived from historical data in combination with technical knowledge of experts and stored as parameter in the simulation model. Small samples (small numbers of regenerated couplings per year) lead to a higher deviation of the simulated probability from the expected value. As the size of the sample increases, the sample average converges towards the expected value due to the law of large numbers [14]. Hence, the expected simulation’s validity of the average cycle time was supposed to be higher for coupling 1 than for coupling 2 (see Table 2). Fig. 1 shows the results drawn from the simulation of average cycle times \( (s_c) \) in comparison to the real mean value \( (x_c) \) for both coupling types \( (c = 1; c = 2) \). The values of the original chart concerning cycle time are normalized due to confidentiality.

![Figure 1: Comparison of simulated and real average cycle times](img)

The diagram shows that the first coupling type’s simulated cycle times show minor simulation deviations (average absolute deviation \( AD_1 < 2.5\% \)). This means that the simulation model produces a good approximation of the real production. The average absolute deviation from the real mean value is calculated on the basis of Eq. 1.

\[
AD_c = \frac{\sum_{r=1}^{R} |s_{cr} - x_c|}{x_c} \times 100.
\]

(1)

Regarding type 2, the difference of the simulations’ results varies significantly. This can be attributed to the large variety of components and low number of annual work load. However, \( AD_2 \) is smaller than 6\%. Considering that this type is the most complex coupling of the MRO company with a lot of stochastic dependencies, the simulation results can be assessed positively (\( AD_c < 10\% \)) [15]. Based on this, simulation experiments were conducted in order to analyze the production and to derive optimal sequencing methods for the MRO process of train couplings.

**Analyzing Production by Means of Simulation.** The branched material flow and dynamic work load in MRO companies frequently lead to missing materials as well as waiting queues and, consequently, to long waiting times in production. Therefore, the cycle time’s proportion of waiting times at the application scenario was determined in 20 simulation runs. It turned out that more than 80\% of the average cycle times were caused to waiting times. However, a distinction between scheduled waiting times and unscheduled waiting times must be made. Scheduled waiting times are expected and considered in the production planning and control (e.g. setup times). In contrast, unscheduled waiting times are not foreseen and clearly lead to extended and fluctuating cycle times as well as to a larger mean tardiness. They result from, for example, machinery breakdowns or missing materials. The average cycle time’s proportion of unscheduled waiting time for both couplings is shown in Fig. 2 (coupling 1: 44\%, coupling 2: 45\%).
In this regard, long unscheduled waiting times appeared during the assembly since this process starts only if all required components are provided. The simulations underline this fact by showing delays in the arrival of certain components. Fig. 3 illustrates this issue for coupling 1 after a simulated period of nearly one year. Of particular note is that the delay of component K forces waiting times on the other components. In order to quickly and easily identify the components that cause the overall longest delays, buffer idle time $t_i$ for each component $i$ of the couplings was measured. Thereby, the buffer idle time comprises all periods of time when the buffer of component $i$ at the assembly’s provision contains no components and is not malfunctioned. In addition, the buffer idle ratio $q_i$ describes the quotient of $t_i$ and the total simulated time $t_{TS}$ (Eq. 2).

$$q_i = \frac{t_i}{t_{TS}} \times 100.$$  

$i = A, Aa, Ab…, Zz$  

This means that $q_i$ decreases over time since $t_{TS}$ grows constantly and $t_i$ increases by the same value or remains stable (e.g. if the buffer is busy or malfunctioned).
In summary, long unscheduled waiting times are caused by components $i$ with a high buffer idle ratio ($q_i > 10\%$ after entire simulated time) since they frequently arrive too late at the assembly. Hereinafter, these components are defined as critical components (CC). The reason for their belated arrivals was found by means of several simulation studies in long waiting queues in front of eight specific work stations (e.g. cleaning, sand blasting). Hence, five standard sequencing rules (see Table 1) were implemented in the simulation model in order to test their impact on the waiting times. The best results were achieved by EDD and JST with an average reduction of $q_i$ of approximately 5% (compared to random prioritization). As long waiting times still occur, a new sequencing method, the fix-and-continue algorithm (FACA) was developed by the IFW to improve this situation. Its main goal is to reduce unscheduled waiting times in production and thus to improve service performance.

**Fix-and-continue Algorithm.** In the following, FACA function is described (see Fig. 4). At first, the CC with the highest $q_i$ is determined and statistically proven by 20 simulation runs. Then, the algorithm uses this component $i$ (CC$_i$) as an initial setup, weighted with the highest priority $p$, ($p=1$, CC$_{ip} = CC_{i1}$). In case of waiting queues on the above-mentioned specific work stations, this component is processed first.

![Figure 4: Step sequence of fix-and-continue algorithm](Geo/69625 © IFW)

The sequencing method leads to a decreasing $q_i$ of this component due to the prioritization, whereas the $q_i$ of other components slightly increases. Hence, the simulation is rerun with updated settings in order to determine the CC$_i$ with the second highest priority (CC$_{i2}$). For this purpose, the variable $p$, which describes the order of priorities, is incremented by 1 prior to the simulation start. If the simulation run does not find another CC (CC$_i = CC_{i-1}$), the algorithm is terminated. In case of positive results (CC$_i \neq CC_{i-1}$) the priority $p$ of new CC$_{ip}$ is fixed and the value of $p$ is incremented by 1. Afterwards, the algorithm reruns the simulation with updated settings in order to determine new CC$_i$. FACA is supposed to be better suited for MRO operations than standard sequencing rules because, in contrast to them, it aims particularly to reduce unscheduled waiting times, which mainly cause long cycle times (see Fig. 2). The more products and the longer the waiting queues in the MRO process the more effective FACA should be. Since only a few coupling types are implemented in the simulation, the effectiveness of FACA is supposed to be even better in real case.

**Simulation Results of Sequencing Rules.** Regarding Fig. 3, component K shows the highest $q_i > 10\%$ ($q_K = 22.13\%$). Thus, by using FACA it will get the highest priority for the MRO process of coupling 1. As this figure represents states from a running simulation, results returned by the algorithm after three full iterations (FACA loops) are presented in Fig. 5. The results are compared to random prioritization since this corresponds to the current situation at the MRO company. By using FACA, a decrease of all CCs’ $q_i$ was achieved. The value of $q_K$ was improved by approximately 10%, while $q_S$, $q_O$, and $q_V$ were decreased on average by nearly 8%. Non-critical components’ $q_i$ increased by approximately 14%. This did not have a negative influence on the average cycle time since these components still wait at assembly’s provision for CCs.
In Total, 140 simulations were run to evaluate the impact of five standard rules (FIFO, EDD, SPT, LPT, JST) and of FACA in comparison to random prioritization. Thereby, the same rule was implemented on every relevant workstation for 20 simulation runs. Table 3 shows the impact of the investigated sequencing rules concerning the service performance of the real case MRO scenario.

Table 3: Impact of sequencing rules on service performance

<table>
<thead>
<tr>
<th>Key Performance Indicator</th>
<th>FIFO</th>
<th>EDD</th>
<th>SPT</th>
<th>LPT</th>
<th>JST</th>
<th>FACA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average cycle time</td>
<td>-2%</td>
<td>-3%</td>
<td>-1%</td>
<td>-2%</td>
<td>-3%</td>
<td>-6%</td>
</tr>
<tr>
<td>Mean tardiness</td>
<td>-9%</td>
<td>-12%</td>
<td>-6%</td>
<td>+3%</td>
<td>-14%</td>
<td>-18%</td>
</tr>
<tr>
<td>On-time delivery</td>
<td>+1%</td>
<td>+2%</td>
<td>-1%</td>
<td>-3%</td>
<td>+2%</td>
<td>+3%</td>
</tr>
</tbody>
</table>

JST led to the best results from standard rules with 3 % decrease of average cycle time, 14 % decrease of mean tardiness and 2 % increase of on-time delivery. Similar achievements were obtained by using EDD and FIFO. By using FACA the results were further improved. The average cycle time was decreased by 6 % and the mean tardiness was decreased by 18 %. Furthermore, an increase of on-time delivery by 3 % was achieved. The LPT rule had the worst performance since the average cycle time increased by 3 % and the on-time delivery decreased by 3 % in comparison to random prioritization. Of particular note is that the SPT rule decreases the on-time delivery by 1 % although it decreases the average cycle time by 1 % and reduces the mean tardiness by 6 %. A possible reason could be that SPT reduces cycle times of long delayed couplings, which still cannot be delivered on-time and slightly increases cycle times of couplings, which were marginal on-time.

Conclusion and outlook

The MRO has to deal with unknown condition of products’ individual components as well as with dynamic and branched material flow. Thus, an efficient production control is complicated even though it is urgently needed since long unscheduled waiting times reduce the service performance. To improve this situation, simulation-based approaches for sequencing provide a way of testing the impact of different methods on the performance and of developing specific algorithms for MRO processes. An event-driven simulation model of a real-case scenario, the MRO of train couplings, was generated and validated. Afterwards, a new sequencing method was developed to
systematically reduce unscheduled waiting times. Based on the idle times of specific buffers in assembly and the simulation time, it determines the most effective prioritization order of the couplings’ components. Furthermore, the simulation model was used to compare five standard sequencing rules with the new algorithm. In this comparison, the potential of the algorithm was revealed for the reduction of unscheduled waiting time, average cycle time and, in particular, mean tardiness as well as for the improvement of on-time delivery. The performance of FACA is supposed to be better, the more coupling types and the higher the machine utilization.

Combinations of rules, applied on different work stations, are not considered in this paper. The author currently investigates the impact of this approach. In addition to that, further research should be dedicated at validating the developed sequencing rule for MRO operations with other real cases.

References


