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Simulation-Based Evaluation of Scheduling Policies in Multi-Stage Production Lines

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Abstract

Productivity and responsiveness in today's manufacturing industry is a product of the scheduling policies in place. As technological advancement dictates speed and reliability, organizational effectiveness is dependent upon an organization's ability to respond through strategic planning. This research focuses on the simulation-based evaluation of multi-execution stage scheduling policy within multi-line production systems. In the presented case, each production scenario within the specified time limit was modeled using discrete event simulation, tested with different scheduling policies of FCFS, SPT, EDD and productivity assessment with varying workloads and operational conditions. Data captured through simulation included system throughput, delays, average job completion time, resource utilization, and number of delays. The overall industry perception is that SPT consistently outperformed other policies with lowest average reachability milestones SPT performance while EDD showed superior performance on meeting deadlines more effectively, outclassing SPT in lack of setting volatility. The disguise of efficiency against predictability sheds light beyond the schedule policies and their efficiency evaluation aids finding the policy's transcend from hypothesis to execution anticipating reframing response beforehand resulting circumvent least impact on altering production goals through agile change improvements to processes seamlessly enable modifying targeted disturbance within untouched workflow designed areas freely redefining targeted zones crafted to facilitate disturbance altering zones streamline processes. These findings reaffirm the importance policy-making in operational processes simulation, marking untouched grounds for work combining machine learning, real-time system optimization, and simulation.

Keywords: Multi-Stage Production, Discrete Event Simulation, Scheduling Policies, Production Lines, Job Scheduling, Manufacturing Systems, Process Optimization, Operations Research.

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Introduction

To stay competitive in rapidly changing market environments, multi-stage and complex production lines must operate at peak efficiency and flexibility. As an essential part of production planning, scheduling selects the sequence and timing of jobs on the different machines. Undesirable scheduling practices are responsible for a myriad of problems such as congestion, excessive lead times, poor delivery performance, and low resource utilization, all of which weaken profitability and customer satisfaction. Interconnected workstations that specialize in specific tasks make up multi-stage production lines. From the overview given, jobs progress simultaneously and dependently with each other as limited by machines, setup times, and product priorities. All these factors combine with the numerous job requirements along with differing processing times and machine capabilities to add complexity to scheduling decisions. There is no universally applicable answer to scheduling challenges in such scenarios. This demonstrates the need for a holistic approach that will devise new policies to determine dominant strategies and measure scheduling effectiveness using data within the researched boundaries. Contemporary automated scheduling methods omit consideration of production environment disruptions along with demand, resource availability fluctuations, or shifting focus altogether, compromising the needed flexibility in contemporary manufacturing. Equally bad events on the other side of the fence occur in the realm of theory. Simulation-based approaches offer more promising results. With this approach, 'what-if' scenario analyses and sensitivity evaluations can be performed on live production systems which would otherwise be unfeasible. Simulations provide a risk-free virtual environment for systems monitoring, allowing for the testing of real-world scenarios without disrupting them. This study aims to enhance the optimization of dispatching rules on multi-stage production lines with discrete event simulation (DES). We focus on four prominent scheduling policies: First-Come-First-Served (FCFS), Shortest Processing Time (SPT), and Earliest Due Date (EDD). These policies differ in job execution prioritization leading to unique results based on the production environment of the system. By simulating the system under different scenarios, we are able to study how these policies impact performance indicators such as throughput, idle time (both on the machine and in the system), job tardiness, and system resource utilization. This research offers practical strategies to address operational challenges faced by manufacturing companies. Planners often grapple with trade-offs related to optimization for speed, cost, and reliability. Having deeper insights into the different scheduling policies allows for better production planning aligned with strategic objectives. In addition, our simulation framework is built to be easily modified or enhanced by other users with custom scheduling policies or external optimization tools. This paper is organized systematically. First, the literature survey offers an extensive summary of prior works in scheduling and simulation; secondly, the methodology chapter describes the configuration of the simulation and the execution of policy in the simulation; results and discussion evaluate the data collected from several iterations of the simulation; and lastly, the conclusion presents the analysis alongside identifying gaps, while offering additional insights for subsequent research initiatives.

Literature Survey

Research on the domain of job scheduling in multi-stage production lines has been done thoroughly because of the practicality it serves for the manufacturing processes. Earlier works like, focused on the core principles of deterministic scheduling. More recent approaches have added stochastic and dynamic features to mimic real-life uncertainties. This literature survey focuses on simulation-based approaches and scheduling strategies comparisons from 2000 to 2021. (Pinedo, 2008) analyzed different scheduling models providing a comprehensive overview while focusing on long-term multi-stage systems. His approach highlighted the growing complexity and pose adaptive multi-stage systems followed by enhanced strategies needing comprehensive systems. This work advanced static scheduling models with real-time decisions for dynamic control. (Jain & Meeran, 1999) also evaluated classical heuristics SPT and EDD in flow shop scheduling, which highlighted varying performance based on the particular job mix and system configuration. (Fang & Xi, 2003) demonstrated the need for simulation-based optimization in job shop scheduling, claiming simulation is a better fit than analytical models for depicting complex systems. Their approach concerning machine breakdowns and changes in priority provided great value in outcome evaluation and inspired others to use discrete event simulation (DES) for production analysis. compared heuristic and rule-based strategies in arena simulation focusing on the multi-stage environment. They found that EDD prioritization was more useful for meeting deadlines, while SPT improved average processing times. This echoing the previous findings by (Blackstone et al., 1982), who emphasized the multi-condition applicability of rules claiming that no single rule works optimally with all conditions. More recently, (Yassine & Chelbi, 2016) coupled simulation with lean thinking to analyze production scheduling in multi-stage systems. System-wide throughput had to be balanced with job-level performance metrics at the same time. Also, business objectives of order competitiveness, such as late orders and maximized machine utilization, need to be considered for scheduling policy alignment. With the advent of Industry 4.0, dynamic scheduling garnered attention. (Zhan et al., 2019) applied intelligent control to simulations by adding feedback loops

that dynamically alter schedules in real-time. Such an approach aims to fulfill digital twin principles of being perpetually open for enhancement. Finally, (Kumar & Jain, 2020) compiled simulation studies focused on scheduling in flexible manufacturing systems. The hybridization of rule-based scheduling with machine learning or optimization techniques was noted, focusing on the use of adaptive systems. These models combine the best of both worlds of rigid structures and unpredictable, non-adaptive systems. As a whole, these studies illustrate the power simulation has in the context of scheduling policies within more advanced manufacturing systems containing multiple interrelated processes. Even though classic heuristics are still important, the latest approaches prefer them to be more flexible and based on available data. We address this gap by performing simulation-based policy benchmarking for a multi-stage production line and analyzing the inter-shift performance trade-offs under different workloads.

Methodology

This study uses discrete event simulation (DES) to analyze a relative multi-stage production line simulation to test the effects of different scheduling policies. The system contains five sequentially interdependent workstations which serves as steps in the production process. Jobs enter the system with a pre-defined set of processes needed to be completed, the processing queue, and deadlines aligned with the expected norms in the industrial production ecosystem. The simulation was constructed in Arena Simulation Software. The model accounts for periodic arrival of jobs where each job encompasses five stages of relayed activities. Each stage processes tasks for a period which varies randomly between a lower and higher value set, whilst there are limited buffer spaces between stages in order to create scenarios of queueing and delay. The strategies designed included: First-Come-First-Served (FCFS), Shortest Processing Time (SPT), and Earliest Due Date (EDD) and tested. Each policy dictates the order in which jobs will be served by the next open machine on every workstation. FCFS places jobs in an order dictated by their order of arrival, SPT selects the work item which has the least amount of work left to do on it, and EDD places priority to the jobs which have to be finished the soonest. Performance metrics tracked in during the simulation include throughput or volume of completed jobs, average job completion timing, the proportion of jobs completed within the expected timing, the amounts of work hours utilized for the machines, and average amount of work left waiting in line at each workstation. Each policy was run for 10,000-time units, which amounted to running the simulation for 10,000-time units, which was sufficient for gleaning meaningful insights for data analysis and comparison. In their attempts to achieve uniformity and consistency across the board, all simulations incorporated the same patterns for job arrivals with respect to processing requirements. In addition to the above, warm up periods were used to mask the effects of initial conditions and multiple replications were performed to enhance statistical reliability. The outcomes of the simulations were compiled and analyzed utilizing aims of Microsoft Excel alongside other advanced statistical and analytical software packages. The primary focus of comparative analysis was to assess each scheduling policy and outline the respective advantages and disadvantages for the scheduling policies under the given conditions. The findings are outlined in the next section which is also accompanied with various graphs and tables that serve to illustrate the most important differences in performance metrics.

Results and Discussion

The simulation output offers valuable observations regarding various scheduling policies over major metrics. From the simulation results, the performance metrics for FCFS, SPT, and EDD are presented in Table 1.

Table 1: Performance Comparison of Scheduling Policies

Metric	FCFS	SPT	EDD
Average Job Completion Time	52.3	38.7	45.6
Jobs Completed on Time (%)	67.4%	72.8%	89.1%
Machine Utilization (%)	84.5%	87.2%	86.4%
Average Queue Length	8.2	6.4	7.1
Total Jobs Completed	192	210	202

The SPT policy is the best in minimizing average job completion time and maximizing throughput according to the table. This looks correct from a theoretical standpoint because SPT has been shown to minimize delays in the system because it processes queues in order of shortest time to completion first. However, assignment of work based on deadlines is not accommodated by SPT which translates to a poorer rate of timely completion when compared to EDD. The EDD policy has the highest percentage of on-time delivery and serves well in environment operating under strict deadlines. Although SPT completes work faster, EDD strikes a balance between efficiency and deadline focus. While FCFS scheduling has the advantage of being easy to use, it is always the worst in comparison to others in all metrics but especially in heterogeneous systems with differing job sizes and due dates. A bar graph is presented in Figure 1

which illustrates the average completion time for jobs in the three policies with respect to achieved averages over time as the system evolves dynamically.

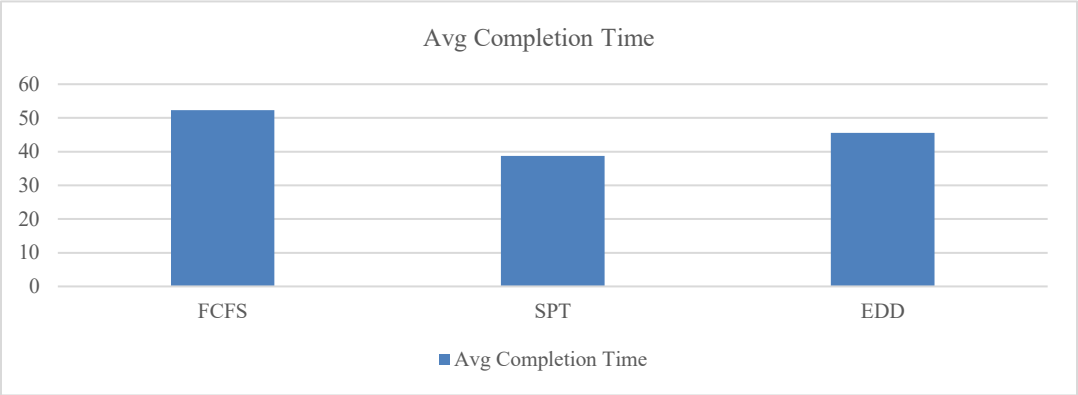


Fig. 1: Average Job Completion Time for Different Scheduling Policies

The completion time benefits provided by SPT are clearly marked in the graphical illustration. Nonetheless, policy choice should be based on organizational focus areas. In cases where meeting delivery obligations is of utmost importance, EDD, despite having longer average completion times, may still be the better option. As a whole, the approach using simulations provides value in the form of quantitative evidence in the evaluation of planning policies using scheduling algorithms. It aids in understanding the balance between conflicting objectives and helps manufacturing planners to devise strategies that optimally resolve scheduling conflicts.

Conclusion

The multi-stage production lines shown in this research highlight the effectiveness of simulation-based analysis with regards to evaluating scheduling policies. With a controlled production environment simulated, outcomes were realized from varying the FCFS, SPT, and EDD strategies. Defintie differences were seen in cross various operational metrics. Regarding throughput and average completion time, SPT did seem to outperformed the others and EDDs showed better adherence to deadlines. While FCFS did receive zero marks on the simplicity metric—due to being the simplest scheduling strategy—they were still outperformed on every measurable metric. These results show how AI based strategic decision making simulation aids context sensitive scheduling within a system. Adding machine failures and dynamic job arrivals variables could mark the model's improvements. Implementing AI or reinforcement learning could in fact enable responsive scheduling based solutions.

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