Maximizing Throughout: Leveraging Meta-heuristics for Plant Scheduling
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Production scheduling, or allocation of machines and resources to operations, plays a critical role in planning and implementing an efficient, flexible, and profitable manufacturing system. It is an operational level decision, which helps optimize capacity utilization and maximize output when executed systematically. The complexity of scheduling in a plant increases due to machine flexibilities and precedence relationships between operations within a job. Hence, traditional techniques such as Johnson’s n/2 method, priority rules, and other heuristics might be insufficient for providing an optimized schedule. In such a complex situation, meta-heuristic optimization is a dynamic technique for effective and efficient decision making.

This paper discusses the various issues associated with scheduling in a manufacturing environment, and how best to resolve them. Our proposed solution is a scheduler built on a set of meta-heuristics (MH) for optimal scheduling. We have used a numerical example to illustrate the efficacy of the proposed algorithm. On comparing the results with those obtained from applying traditional priority rules, we found that the proposed approach achieves greater optimization.
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Introduction

To operate an efficient and profitable system, manufacturers need to clearly define key decision points and carefully assess their importance. The challenges associated with decision making in a manufacturing system span four important stages: designing, planning, scheduling, and control.¹ Scheduling of operations is one of the most critical tasks in the planning and management of manufacturing processes. The typical performance indicators for scheduling are mean flow-time and throughput, make-span, and tardiness.

Though robust schedules lead to better system performance, the flexibility of machines makes production scheduling a difficult combinatorial optimization problem and nondeterministic polynomial (NP) hard. It is therefore recommended to use heuristic methods when solving such difficult problems.

While many studies have adopted mathematical programming techniques to solve scheduling and assignment problems in a manufacturing system, researchers these days use artificial intelligence optimization methods known as meta-heuristics. These include genetic algorithms (GAs), Tabu search, ant colony optimization, and particle swarm optimization.² These studies clearly indicate that meta-heuristics enables manufacturers to handle scheduling problems effectively. To solve the scheduling problem in a flexible flow shop, researchers have proposed a combined approach of Taguchi experimental design³ with meta-heuristics and hybrid meta-heuristics.⁴ Similarly, we examine operational-level decision-making (scheduling with precedence relationships between operations) and demonstrate how meta-heuristics helps solve problems in shop-floor production scheduling—one of the most difficult combinatorial optimization problems.

Optimal Production Scheduling for Promoting Efficiencies

An efficient and streamlined production plant is critical for manufacturers. Long-term business sustainability and profitability depends on effective shop floor performance, which is in turn determined by the quality of production schedules. Efficient scheduling helps in preparing a well-planned calendar for handling a set of jobs, which enables manufacturers to reduce production time and costs.
As a part of production scheduling, manufacturers are required to make key decisions on a continual basis, as depicted in Figure 1.

Therefore, they require a good production scheduling technique to identify resource conflicts, control job allotment to shops, replenish raw materials in time, ensure delivery fulfillment, and plan preventive maintenance at appropriate times. An effective schedule helps manufacturers synchronize the extended production network through accurately projected and updated job finish dates.

An adaptable and well-oiled system helps achieve greater productivity on the shop floor. Even when faced with large production volumes, uncertain circumstances, or limited resources, manufacturers can use production scheduling techniques to quickly modify production schedules and maximize overall production efficiency. It is also important that they create short-term production plans with reliable schedules for operations spanning a few days or weeks.
The Challenge Posed by Production Disruptions

Production plants function in a complex and dynamic environment where the possibility of disruptions is high. Real-time disruptions impact the smooth running of manufacturing plants. Typical disruptions can be:

- **Resource related:** Breakdown of machines, unavailability of the operator, excessive loading limits, shortage of materials, and defective materials
- **Jobs related:** Rush jobs, job cancellation, changes in due date, uncertainty in arrival of jobs, and shift in job priorities

Scheduling problems also arise when shared resources like labor, raw material, and machines need to be used to make different products at the same time. A dynamic scheduling system can address these challenges effectively, and help floor managers make optimal decisions.

Making Optimal Decisions by Adopting Dynamic Scheduling Techniques

To meet a scheduling challenge effectively, plant managers have depended on a range of tools such as Gantt charts and histograms that help understand and analyze the data from production systems. However, in recent times, meta-heuristic search principles and methods such as simulated annealing, Tabu search, and genetic algorithms are increasingly being applied to a range of combinatorial problems such as production scheduling. These methods often work as an iterative master process.

Meta-heuristics maximizes the search for an optimal solution by avoiding the possibility of a local search being restricted by local optima. Typically, local search begins from a specific solution and moves iteratively to a better solution in a defined neighborhood of the current solution; the search ends on reaching a local optimum, that is, a better solution cannot be found in the immediate neighborhood. However, MH extends the local search algorithm beyond providing initial solutions to ultimately escape local optima.

Leveraging MH enables manufacturers to plan reliable and strong plant schedules that decentralize the control of the manufacturing system, reduce complexity and cost, and increase flexibility as well as flaw tolerance.

Understanding a Typical Production Scheduling Problem

To build a streamlined scheduling system, we need to first carefully formulate a problem encompassing plant-specific constraints, then validate the formulation, and finally design algorithms using mathematical techniques.

As part of our study, we analyzed machine flexibility or a flexible manufacturing system (FMS) problem to understand how it can be solved effectively using meta-heuristics. The implemented meta-heuristic is a genetic algorithm based on the Darwinian mechanism of ‘survival of the fittest.' Given here is a high level
algorithmic framework that helps develop heuristics optimization algorithms, which can be used to solve specific scheduling problems.

The key assumptions for planning this exercise include a fixed number of machines, the known number of operations for each part, processing time for each operation, and available machines for each operation. The set-up time is not considered.

The problem is to assign each operation to an available machine and sequence the operations assigned to each machine. The performance measure considered is ‘make-span’ (MS). The mathematical expression for MS is derived as follows:

Notations

\( i = \) number of parts, \((i=1,2,3..n)\)
\( j = \) number of machines, \((j=1,2,3...m)\)
\( k = \) number of operations,\((k=1,2,3...K)\)

Parameters

\( n = \) number of parts
\( m = \) number of machines
\( K_i = \) number of operations at part \( I \)

\( C_{ijk} = \) the completion of time of \( k^\text{th} \) operation of part \( I \) at \( j^\text{th} \) machine

The objective is to measure performance by minimizing the make-span for an optimal schedule. Mathematically, **MS is the sum of the completion time for all jobs**. Completion time in turn can be defined mathematically as the sum of all the required operations for each part:

\[
C_{\text{max}} = \sum_{i=1}^{n} \sum_{k=1}^{K} C_{ijk}
\]  

{1}

Therefore, the objective function can be defined as:

\[
\text{minimize} \ (\text{MS}) = \min(C_{\text{max}})
\]  

{2}

The solution for such a problem, involving no preemption of jobs, can be represented by an optimal job sequence that results in the smallest MS.
Designing a Meta-heuristics-based Plant Scheduler

To enable manufacturers to overcome production scheduling problems and achieve more productivity and efficiency, we developed a meta-heuristic approach for a plant scheduler on a Java™-based platform. The scheduler uses a simple algorithm to schedule jobs on priority. It creates a class of schedules containing at least one optimal schedule to achieve a minimal make-span.

The optimization approach of the proposed MH follows the process depicted in Figure 2.

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<th>Step</th>
<th>Action</th>
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<td>1.</td>
<td>Generate the initial schedule by considering the available machines and the precedence relationship of operations, and determine the size of the feasible schedules and the maximum number of iterations in the generation schedule</td>
</tr>
<tr>
<td>2.</td>
<td>Calculate the make-span value of each schedule that was initially generated</td>
</tr>
<tr>
<td>3.</td>
<td>Determine the selection probability of each schedule of the initial population</td>
</tr>
<tr>
<td>4.</td>
<td>Select a pair of members (parents) that can be used for reproduction using the selection probability</td>
</tr>
<tr>
<td>5.</td>
<td>Explore the search space to find more feasible schedules with less make-span time and replace the worse schedule with new and better schedules</td>
</tr>
<tr>
<td>6.</td>
<td>Stop if the current generation is equal to the maximum number of the iterations in the generation schedule, else move back to Step 2</td>
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*Figure 2: Process flow for optimizing make-span using the proposed meta-heuristic*
Applying the Proposed Solution to an Illustrative Example

In order to demonstrate the effectiveness of our proposed scheduler over traditional techniques, we considered a hypothetical manufacturing system:

- The system consists of five machines and a centralized buffer. The buffer helps avoid deadlocks.
- Five distinct parts, each requiring twenty operations, are processed in the system. We assume that the processing time for each operation at each machine is known.
- There are precedence relationships between each of the five distinct operations for the parts. These relationships show the sequence of operations required for each job.

We also made assumptions regarding the availability of raw material and resources, and predetermined processing times. We assumed there is no delay between two machines, and that a central buffer with infinite capacity to avoid any deadlock is available. The proposed meta-heuristic was then tested with the help of an illustrative example.

Numerical Analysis of the Illustrative Example Using a Scheduler

To solve the complex problem under consideration, we developed a Java™ based scheduler, which encompasses the functionality to change a job parameter as well as a model parameter. The scheduler uses the traditional ‘Last in First out’ (LIFO), ‘First in First out’ (FIFO), and Shortest Processing Time (SPT) methods of scheduling, and compares them with the proposed MH approach. The Gantt chart for the proposed approach is shown in Figure 3.

Figure 3: Gantt chart of make-span – color-coded by each part used in the illustration
The chart shows that the make-span obtained using the proposed approach is 51 time units. It also clearly indicates the allocation of machines for the various operations according to the precedence relationship. A comparison of the make-span derived from the proposed MH-based approach with those resulting from traditional rules is represented in Figure 4.

From Figure 4, we can conclude that for the given scheduling problem, meta-heuristics provides the schedule with minimum make-span (51 time units), whereas LIFO provides the maximum make-span of 88 time units. While SPT is more effective than FIFO and LIFO, meta-heuristics proves its superiority over all other approaches.

Figure 4: Comparison of make-span derived from meta-heuristics with traditional rules shows that MH produces the most optimal make-span

Figure 5: Meta-heuristics helps achieve better results as compared to traditional rules
We also tested the developed plant scheduler for more complex problems (40 part types and 20 machines with 160 operations). From the graph in Figure 5, it can be observed that the proposed approach using meta-heuristics consistently performs better than other solutions that employ traditional techniques. LIFO again emerges as the worst performer. There is also a clear indication that the proposed approach is more robust with the ability to perform effectively even in a complex environment.

Conclusion

As robustness, stability, flexibility, adaptability, and efficiency become buzzwords in the manufacturing industry, it is essential that production plants be optimized with streamlined schedules. There have been significant advancements in factory automation, as well as improvements in the flexibility and accuracy of controlling machines for reconfiguration and rescheduling. One of the biggest implications of these developments is the need for creating fine-tuned plant schedules in near real-time. Manufacturing plants are leveraging advanced software systems and optimization algorithms that strengthen production scheduling.

Our study shows that meta-heuristics is a powerful tool for addressing complex production scheduling problems. In particular, its ability to optimize complex job-shop problems results in significant business benefits such as reduced time and costs, and improved production efficiencies. By leveraging meta-heuristics, organizations can develop the most optimal solutions and reliable plant schedules to improve productivity, increase operational flexibility, and build efficient manufacturing systems.

However, this scheduler is best suited to manufacturing scheduling, and cannot be used across the supply chain. The technique can be enhanced through the amalgamation of two meta-heuristics. To arrive at more comprehensive insights and approaches, we suggest adding more realistic parameters such as machine breakdowns, outages, and delays in sourcing raw materials.
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