Scheduling for Flexible Production: A Case Study of Production Leveling under Volume Constraints

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Abstract. Flexible manufacturing systems in high-mix low-volume segments offer many challenges in terms of planning and scheduling. The complexity of these systems often requires a systemic approach for which humans are the perfect actors. However, computer systems can support scheduling tasks more effectively due to their capacity to synthesize large amounts of data. This paper describes a system developed for the flexible manufacturing of wooden doors with a wide range of product configurations. This paper proposes a rule-based scheduling method for high-mix production. The method was applied and validated at a wooden door producer. Based on the company's production schedule for a given week, a scheduling program was developed that suggested minor rearrangements for production leveling. As the rule-based approach makes the decisions verifiable, the program was validated at the producer, through a case study of production leveling under volume constraints. The results include the complete elimination of changeovers and the stabilization of throughput, which improved the precision of the delivery time. The producer is integrating the program into their production planning and control system. Thus, the results suggest that the proposed method can be useful for scheduling high-mix low-volume production, and merits further validation in similar environments.

Keywords: Production leveling, Production optimization, Scheduling, Explainable AI.

1 Introduction

Due to the complexity of modern manufacturing systems, planning and scheduling for production leveling is a difficult task for humans. As more capabilities and constraints are added to the manufacturing system, more dimensions are also added to the scheduling task. Computers can solve multi-dimensional problems such as manufacturing scheduling far easier than humans [1].

On the other hand, the creativity and flexibility of the human mind coupled with tacit knowledge and experience often reveal challenges and opportunities that a computer cannot possibly find unless explicitly programmed to do so. This human touch to scheduling is crucial in flexible manufacturing systems where the design of robust rules for computer-automated scheduling may not be feasible. Utilizing the best of both worlds,

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this paper presents a combined approach to production scheduling where a rule-based system informs an engineer of possible improvements to scheduling. The remainder of this paper is structured as follows: Section 2 provides a brief insight into the related theory and larger context before the methodology of the research work is described in section 3. Section 4 introduces the case study, and the results are presented in section 5. A discussion is made in section 6, and finally, conclusions are made in section 7.

2 Production scheduling

Production scheduling is defined as a set of orders to be performed to best satisfy a set of criteria. The criteria involve tradeoffs between early and late completion of an order and reserving machines for the order and frequency of production changeovers [2].

Production flexibility results from the adaptability inherent in processes. Typically, it is the material handling that limits the flexibility as a result of the finite capacity of storage buffers and transport systems [2].

As product variation and production constraints increase, production scheduling becomes increasingly complex and requires more flexibility [3]. Balancing the production flow throughout the manufacturing system improves production efficiency [4]. When one process takes longer to set up than the others, this process becomes a bottleneck. In manufacturing systems with high product mix, proper scheduling may alleviate the effects of this bottleneck by minimizing the number of changeovers. However, maximum throughput is not the only objective in manufacturing as quality is a prerequisite for success [5]. Thereby, production scheduling must preserve the required product quantity and quality, two notoriously conflicting objectives.

Methods have been developed to handle basic scheduling operations, and these are widely available in commercial computer systems [6]. In academia, heuristics and meta-heuristics have been applied to many problems in planning and scheduling [7]. A simulation study by Haeussler and Netzer [8] indicates that rule-based heuristics may outperform optimization-based approaches at high utilization rates, i.e. close to production capacity. The multitude of available information from new technologies adds to the complexity of scheduling in modern manufacturing systems [9]. However, manufacturers operating in environments with high product mix and low volume may struggle with finding an "off-the-shelf" solution for their scheduling tasks, because the problems are non-trivial and often unique. Therefore, scheduling for such environments is often a manual task.

An alternative way to control scheduling in a flexible manufacturing system is to treat the system as a holonic manufacturing system [10]. Holonic manufacturing is a highly distributed control paradigm based on autonomous 'holons' like order holons, product holons, and resource holons. Unlike traditional methods, a holonic system is not constrained to an already established schedule. A holonic system triggers an update when new expectations arise, and was explored further in later publications [11,12].

3 Methodology

A rule-based heuristic was developed using Python3 in a Jupyter Notebook environment. Besides the Python3 built-in libraries, the packages Numpy and Pandas were used for data analysis, and Matplotlib was used for visualizations. The production schedule for three days from the wooden door company was first used to develop an initial version of the method for proof of concept. Upon acceptance, the production schedules for five days, which the company experienced as particularly challenging, were used to make further improvements. An executable program was generated from the code and validated on real data within the manufacturing environment.

The dataset for the five challenging days is used in this paper to demonstrate the developed method. The dataset contains 130 customer orders, where 64 orders contain painted products. A total of 2131 products are included in the dataset, of which 981 are painted. There are 39 unique colors. Fig. 1 shows the number of products and the number of colors in each day in the dataset.

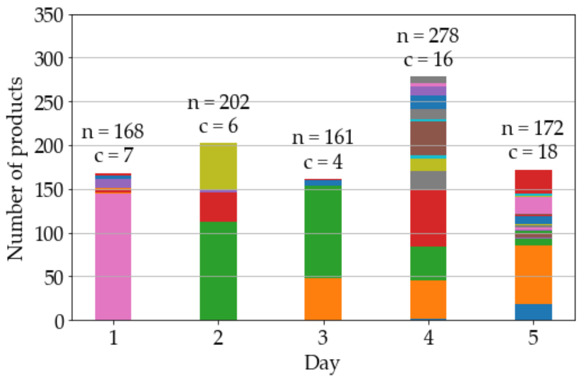

Fig. 1. Number of products of different colors per day (initial schedule). The colors are only a representation of the different product colors and are not the same as the true colors. n signifies the total number of products, and c signifies the number of different colors.

4 Case description

The case company manufactures a wide range of door variants. The company is situated in a highly volatile market with large fluctuations regarding order sizes and product configurations. To meet the demand, the company has developed a flexible manufacturing system capable of accommodating most order types with a high degree of automation. This system relies heavily on batching products of similar configurations to limit the number of changeovers at critical bottlenecks such as the painting machine.

The painting machine holds a limited number of colors and requires cleaning for each set-up. It is therefore beneficial to allocate all products of the same color to a single day, however, certain limitations and considerations must be made which complicate this initially simple rule:

- A single order may contain doors of different colors

- All the doors in an order must be painted on the same day, but not necessarily at the same time during the day, thus a mix of orders is allowed
- Maximum capacity of the production line is 500 doors per day
- Maximum capacity of the painting machine is 200 doors per day
- Maximum number of available colors for the painting machine is ten
- At the time of scheduling, the delivery date of each order is estimated based on overall capacity, etc. To avoid large deviations from the estimation given to the customer, orders can only be rearranged within their assigned week.

Currently, the colors of produced products are automatically determined from the overall system capacity without any regard to the painting machine. Consequently, there is a risk of too many different colors being assigned to a single day, leading to large changeover times for the painting machine, and since the painting machine is the bottleneck it will delay the entire production line. Hence, there is a large potential in moving orders to gather all instances of the same color in a single day.

5 Results

The proposed method consists of four steps: (i) collate colors, (ii) reduce the number of colors per day, (iii) reduce the number of products per day, and (iv) final adjustments.

The following sections describe each of these steps and demonstrate their performance on the dataset with five challenging days. Fig. 2 depicts the status after the various steps.

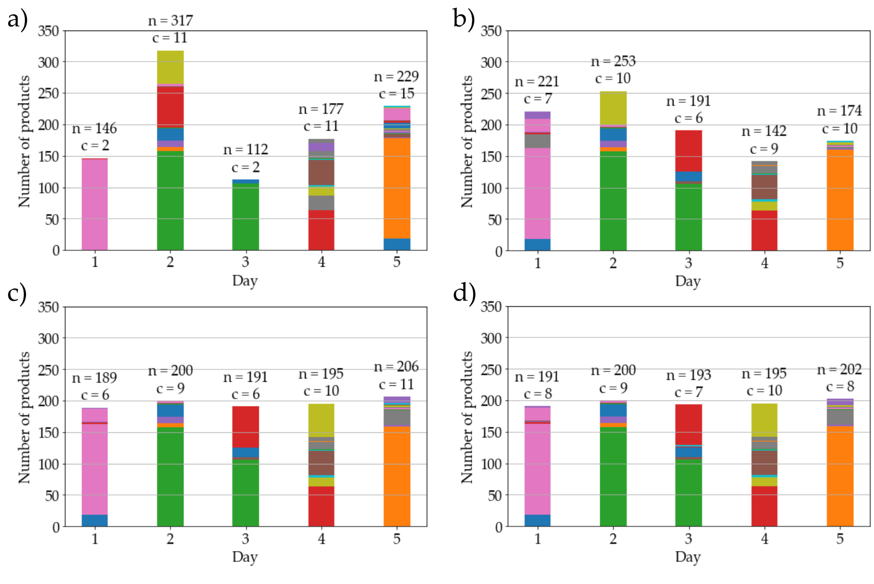

Fig. 2. Number of products (n) and colors (c) each day. **a)** after collating colors, **b)** after limiting the number of colors per day, **c)** after limiting the number of painted products per day, and **d)** after final adjustments.

5.1 Collate colors

The first step of the process is to collate the colors. This is done for each color by identifying the number of instances of the color per day. Next, the possibility of moving colors from the day with the most instances (D_{max}) to the day with the least instances (D_{min}) is considered. This will either result in the move being executed, or D_{max} being excluded from further analysis. At this step only the total capacity of the machine is considered, i.e., if there are enough instances of a single color to exceed the capacity of the machine, this color is not moved to a single day, and production is allowed to continue over several days. This is indeed the case for white doors of which there are many.

Thirty orders were moved to other days to collate colors. This procedure reduces the average number of colors per day from 10.2 to 8.4. While 10.2 colors mean that changeover is required during production, an average below 10 means that the set-up potentially can be done before production starts and thereby enabling continuous production through an entire day.

As illustrated in Fig. 2a, the distribution is not better after this operation where day 2 exceeds the daily capacity of the painting line with 117 doors (58%). Furthermore, on the fifth day, the limit of ten different colors is exceeded by 50%, while days 1 and 3 only have three and two colors respectively.

5.2 Reduce the number of colors per day

To achieve a more even distribution of the colors, the next step reduces the number of colors per day by moving orders from days with many colors to days with fewer colors than the threshold value. This is achieved as follows:

1. Identify the day (D_0) with the largest number of colors
2. Identify the day (D_1) with the smallest number of products
3. Find the free capacity of D_1 (n_{room})
4. Find the color (C) in D_0 based on two conditions: (i) with most instances, (ii) the color C fits in D_1 ($n_C \geq n_{room}$)
5. Move the color C from D_0 to D_1
6. Repeat from point 1 until one of the three criteria is satisfied:
    a. None of the days have more than ten different colors
    b. All days have ten (or more) colors
    c. No days can take on extra products

This procedure proposes to move thirteen orders which reduces the number of different colors per day below the threshold for each day as shown in Fig. 2b. However, the number of painted products per day is not considered during this step. Consequently, the two first days are overloaded by 10% and 25% respectively.

5.3 Reduce the number of products per day

Another procedure is needed to reduce the number of painted products per day to acceptable levels. Because the total number of products entails production close to capacity, a soft limit is imposed on the number of products at this point. This procedure moves three more orders and successfully reduces the number of painted products to a maximum of 206, i.e., only 3% above capacity. This result is shown in Fig. 2c.

5.4 Minor adjustments

To further optimize the production plan, a final production leveling is done. Contrary to the other procedures which target the largest possible orders, this minor adjustment aims at moving only the smallest orders. This change is deliberate to avoid moving orders back and causing a loop. Priority is put on the number of colors per day as violating this limit will imply a changeover during production. The number of painted products, however, only has a linear impact on the total processing time of the day.

Three orders are moved to bring down the number of painted products and the number of colors even further as visualized in Fig. 2d. At this step, only one violation of the initial limits can be observed, which is the 202 painted products on the fifth day. This corresponds to 1% overload and translates to about 5 minutes of extra work.

6 Discussion

The rule-based method presented in this paper progresses in a manner like a human may approach the study case problem. This serves two purposes: not only will it promote explainability, but it will also make the solution understandable to the person who will utilize this as decision support in a scheduling scenario. By presenting the proposed rescheduling operations to the engineer, an informed decision can be made regarding the entire production system, i.e., the effect the new manufacturing plan may have on other manufacturing processes.

The current production plan of the case company is used as the starting point for the demonstrated scheduling method. The original schedule entailed cleaning out the machine to change colors during production. However, the proposed method eliminates the need for changing colors during production, hence avoiding disrupting the production flow. This saves time in set-up as well as materials with associated costs and environmental impact.

The explainability of the proposed method may come at the cost of effectiveness as a stochastic method or a sequential search method may arrive at a better solution, however, the path to that solution may not be straightforward. The proposed method takes a tentative schedule as input as is the current situation at the case company. Starting from an established foundation ensures minimal changes to existing plans, and consequently minimal changes to original delivery dates. For the case company, the painted doors only make up half of the production volume, and there are also soft limits on the total daily capacity of the factory estimated to 500 products regardless of type and configuration. The distribution of all product categories after production leveling concerning the painting machine is displayed in Fig. 3a, where all days are still within the soft limit of maximum of 500 products per day. By applying the same leveling approach for the other product categories, the distribution in Fig. 3b is achieved by moving only eight more orders. The additional moves may further level out the production and improve production flow. These changes must however be carefully considered concerning other manufacturing processes.

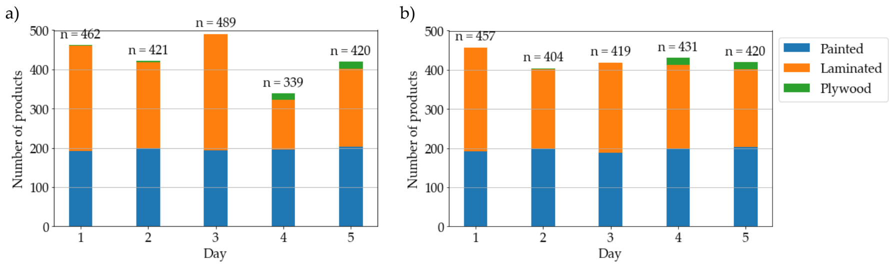

Fig. 3. The number of products scheduled per day per product category. **a)** after leveling with respect to the painting machine, **b)** after additional leveling of other product categories

An alternative approach could start with a clean slate and assign dates to orders as best as possible from the very beginning. This would however mean that only the expected delivery week, not a date, can be communicated to the customer at the time of the order. A similar scenario could be true with a holonic approach for which flexibility could be gained at the cost of predictability in terms of delivery dates. An evaluation should be made on which alternative is suitable for the context; some may prefer a timeframe narrowing in as the time to delivery closes in, while others may prefer to have a fixed date to consider, and rather be aware that this date may change.

7 Conclusions

This paper presented a rule-based method for scheduling in a high-mix low-volume manufacturing environment. This approach makes the results explainable and comprehensible as decision support in flexible manufacturing systems. The case study demonstrates the feasibility of the method in a real manufacturing environment as a tool to inform decision-making processes. The method was shown to minimize the number of threshold violations. Only one day exceeded the limit on the number of painted products, while none of the days exceeded the limitation on the number of colors per day. Consequently, the proposed method resulted in a complete elimination of changeovers during production.

The results have been validated by the case company where the method is being implemented in the existing manufacturing system. The production leveling of the paint line is shown to not have a negative effect on other product categories. Future work involves evaluating the performance on a larger data set and within the production system. Future work will involve a similar rescheduling of other product categories to further improve production leveling. Furthermore, updates based on real-time production data constitute an interesting avenue for future research.

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