Event-driven production rescheduling in job shop environments
Application to sheet metal production processes

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Abstract— **Unpredictable incoming orders and the required nesting process highly complicate production planning and scheduling in sheet metal job shop environments and cause extremely high lead times as well as intermediate stocks. For this, numerous advanced planning and scheduling (APS) algorithms exist, aiming at creating a globally optimized production schedule. Due to the complexity of the multi-objective optimization and the large amount of unforeseen shop-floor events, effective and applicable solutions have not been presented so far. This work introduces an event-driven rescheduling concept based on lean principles leading to a high responsiveness of the production process to *any kind* of deviation. The achieved, significantly smaller buffer occupancies enable shorter lead times and improved delivery time estimations. Excellent performance results of the rescheduling concept are shown in different simulation experiments. The presented concept can easily be implemented in any kind of sheet metal job shop and its respective IT infrastructure.**

I. INTRODUCTION

Decreasing lot sizes, mass customization, fluctuating demand and just-in-time delivery make it more difficult to handle the complexity of job shop production environments. In terms of the Industry 4.0, cyber-physical systems, digital twins and the real-time availability of production data offer new possibilities in integrating IT-support into the production processes. Although much progress has been made in the last years in enhancing single machine tools' productivity, including their automation, overall production processes in job shops have not been improved noticeably and are still rarely executed as planned.

In the sheet metal processing, parts from different orders are optimally nested onto the same sheet metal to minimize waste material in the cutting process. After cutting or punching (using a laser beam machine or a punch press), the parts are removed from the sheets and are sorted. A possible next production step is bending, which often becomes a bottleneck in sheet metal processing [1]. This results in a backlog of orders waiting in front of the bending machines. Workers at the machines lose track of the jobs waiting in the buffer area and their prioritization in the production plan. Usually, they either pick the order which apparently causes the least set-up operations or they search for specific urgent orders in a time-consuming process.

The order accumulation in the bending area has the following disadvantages:

- high intermediate stock and space requirement
- high order lead times
- unpredictable delivery times

A typical procedure of IT-support in metal work job shops, as it is considered in this work, is shown in Fig. 1. After the order creation inside the enterprise resource planning (ERP) system, including the backward calculation of a rough planning for each order based on unlimited resources, the APS aims at improving the nesting process and the detailed scheduling in an integrated way. While executing the APS-schedule on the shop-floor, the event-based rescheduling applies.

In many productions, production planning and control (PPC) systems are introduced to extend the functionality of ERP systems by considering the limitation of machine resources. Due to the high complexity of the planning task, APS systems continue to extend the functionality and aim at creating an optimal schedule by predicting process times as exactly as possible and compiling holistic and global optima. However, the schedules given by current APS systems are not reliable in most cases. The link to the shop-floor is still missing [2] and they take away transparency and flexibility in the order processing. Often, they also lead to uncontrollably complex IT-structures. Continuous corrections of the scheduling postpone delivery times and make their forecast impossible [3].

Schedules created with APS algorithms do not run as planned because of

- the high number of unforeseen events,
- the complexity of multi-objective optimizations and
- human decision making.

The work presented in this paper proposes an approach for handling the mentioned challenges by enhancing the reactivity of the production system. Counteractions of other optimization objectives are avoided, as well as the prediction of process times, that may be disturbed by unforeseen events or decisions on the shop-floor. The concept has been validated in terms of a simulation.

II. BACKGROUND

A. Theoretical approaches

The scheduling problem is of great use for industrial applications. Due to its complexity, it has already been studied for a long time. Various approaches can be found in literature: heuristics, constraint propagation techniques, simulated annealing, genetic algorithms, neural networks, fuzzy logic, etc. [4]. However, these approaches encounter

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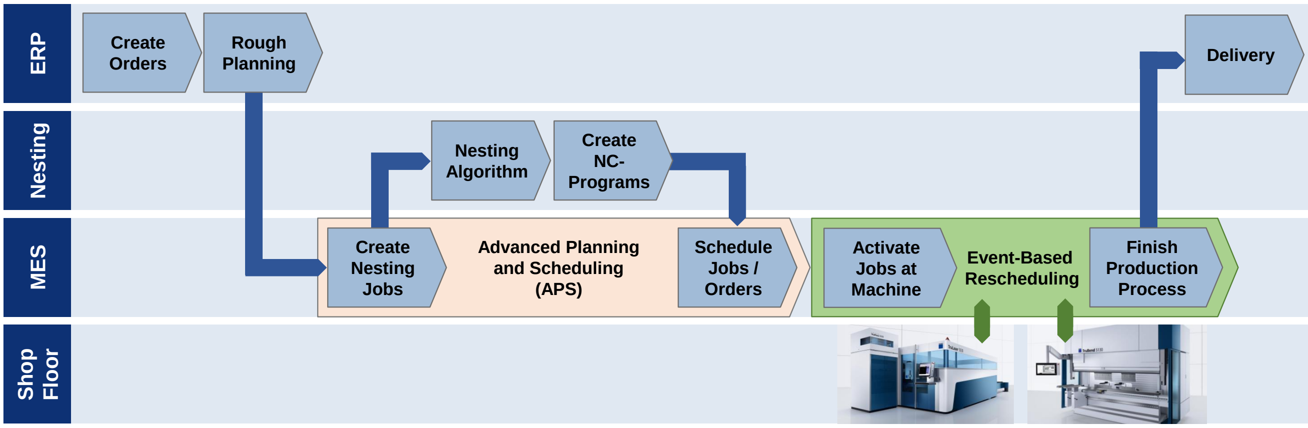

Fig. 1. IT-support in the sheet metal production process and scope of this work: event-based rescheduling (in green)

great difficulties when applied to real-world situations [4], as they use simplistic theoretical models.

The scheduling task can be divided into two stages - the predictive (planning-oriented) scheduling and the reactive (control-oriented) scheduling [5]. The predictive scheduling attempts to create a granular forecast of each operation's process time and to globally optimize this schedule with the result of setting start and end times for all processes. Even a simple deterministic job shop problem is already NP-hard and can only be solved with heuristic solutions [6]. For a classical job shop problem with n jobs and m machines the total number of possible schedules is $(n!)^m$ [7], leading to an extremely high number of possible constellations, even though the necessary nesting has not been considered so far.

For laser cutting machines in the sheet metal industry, the nesting algorithm focuses on minimizing waste material, whereas the order scheduling focuses on maximizing due time fulfillment and overall productivity. Today, these two optimization processes are done sequentially (see Fig. 1). At first, orders with similar due times and the same sheet material are grouped together. Within these groups, the orders' parts are optimally nested onto sheets. Then, the jobs are scheduled on the laser machine as well as on the bending machine. This leads to a sub-optimization, as both processes' goals conflict with each other [6].

In [8], the integration of both processes is approached by grouping the parts for the nesting process, while considering the minimization of time-consuming setups at the bending machine. This means, that parts are grouped for nesting if a bending machine layout can be reused for all of them. The production span can be reduced, but this must be weighed against the possible increase in material utilization. A continuous balance of the cutting and bending process, as well as a unidirectional part flow with only small inventory in front of the bending machine, are required for the usefulness of the approach. If this balance cannot be guaranteed, a *bottleneck-focused optimization* is recommended. [8] requires the execution according to the fixed schedule and does not take into account unforeseen deviations from the schedule, e.g. hot jobs. These are defined as unexpected, urgent orders, that are introduced into the production directly after their creation and are of high priority. [1] extends such integrated approaches by the mentioned bottleneck optimization using local search algorithms. The impact of the real shop-floor situation on the schedule is not taken into account either, though.

B. Shop-floor situation

In terms of Industry 4.0, an increasing amount of real-time shop-floor data gets available for further processing. As cloud computing highly increases computational power, attempts to optimize the scheduling problem mathematically hold great potential. However, scheduling optimization is complex and assumes a lot of neglect. Especially due to unforeseen events, predictive scheduling results are almost immediately subject to changes on the shop-floor [5]. The literature on dynamic scheduling has considered a significant number of these real-time events highly affecting the planned scenario, e.g. machine breakdowns, operator illness, tool unavailability, defective material, hot jobs, job cancellation, due time changes, change in job priority, etc. [9]. Furthermore, neither process plans nor off-line schedules are truly followed on the shop floor [10]. The lack of reactive capabilities is one of the main drawbacks of scheduling systems. It is one of the reasons, why the execution process relies on human operator's expertise, whether a scheduling system is used or not [11]. The component of human decision making and human execution makes reliable predictions even more difficult.

C. Lean production in job shop environments

In the automotive environment, production planning complexity is handled by implementing principles based on the lean production theory. According to the concept of lean production, every operation, except the main operation, has no value [12]. Several crucial lean principles cannot be transferred to the metal work job shop environment, as neither fixed production cycles, nor a one-piece-flow can be achieved considering the varying incoming orders and the required nesting process. However, concepts like the systematical reduction of material stock and lead times are also valid in job shops. The typical queue of buffers, storages and transports have to be questioned and the lead time should serve as a central optimization parameter [13].

III. Proposed Approach

As described in the previous section, there are potentially different solution approaches to the problem. Due to the mentioned obstacles, this work intends to optimize the order processing in sheet metal work job shop environments by developing a reactive scheduling approach based on measurable shop-floor-events. Optimizations based on forecasts of start or end times of production operations are avoided, just as any forecast of processes that might be disturbed by unforeseen events or the forecast of such events themselves. The approach intends to transfer the lean production focus on low lead times and low intermediate stocks to the observed environment. The attention of this paper is restricted to the short-term, event-driven rescheduling and aims for a higher reactivity of the production towards the real-time shop-floor situation.

Considering the high amount of possible unforeseen events influencing the overall production process in various extents, the occupancy of the bending buffer, i.e. the number of orders physically waiting in front of the bending machines to be processed, is selected as control parameter for the production. According to lean principles and the aim for short, predictable lead times, a low bending buffer occupancy represents a well-functioning production process, as the bending operation is the bottleneck in the observed system. Nevertheless, nesting and the aim for minimizing set-up operations at the bending machines lead to a certain minimum requisite buffer occupancy. Selecting the *bending buffer occupancy as control variable* holds several advantages in combination with the presented rescheduling concept:

1. Real-time measurability
2. Aggregation and abstraction of unforeseen events
3. Overall process optimization without counteraction of further optimization objectives

For that, an aimed maximum buffer occupancy, i.e. a target occupancy b_{target}, is determined. If b_{target} is exceeded, the balancing rescheduling process sets in.

A. Benchmark problem

A factory consisting of a laser cutting and two bending machines is a typical layout for a sheet metal job shop and is used as a benchmark production in this work as shown in Fig. 2. At the laser cutting machine, a queue of sheet metals is depicted, waiting to be processed according to the current production plan. Sheet metal parts of different orders are nested onto one sheet. After the cutting process, an operator at the laser machine removes the parts from the sheets and sorts them in the sorting area. If the respective order does not require any further processing, it is transported to the automated storage, being available for delivery. In case of the requirement of a bending operation, the order is moved to the

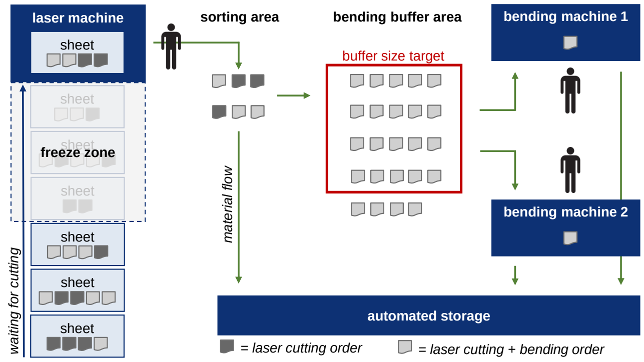

Fig. 2. Production scenario

bending buffer area. This is the place, where the operators of the two bending machines pick the order that is going to be processed next.

The exceeded target of the bending buffer occupancy is indicated in Fig. 2. The rescheduling concept aims at determining actions to avoid a further growing bending buffer occupancy and thus to improve the overall production process. To enable the human operators' flexibility in executing the jobs as well as to ensure enough time for raw sheet commissioning, a *freeze zone* is introduced, preventing the rescheduling of jobs that are already activated at the machines and displayed inside the HMIs. Possible rescheduling procedures are:

- **Rearrangement of staff to the bending process:** Assistance is requested from logistics or the cutting process if the bending buffer contains orders, that cannot be processed by the operator of the bending machine alone due to their part size. Part dimensions are available in the MES as part of the geometry data for nesting.
- **Restorage of semi-finished orders:** The bending buffer is supposed to exclusively contain orders that need to be processed shortly, especially when b_{target} is exceeded. Orders of lower priority, nested onto the sheets due to material utilization reasons, might be restored to ensure the early processing of urgent / overdue orders waiting in the bending buffer.
- **Rearrangement of sheet programs:** The sheets' NC-programs in the production plan, defined as sheet programs, might be rearranged to prevent the extensive cutting of new orders, that require bending operations. Sheets, that contain less bending parts and respectively more parts that are cut only, are preferred in the production sequence over sheets with a big amount of implied bending operations. This way, the strain at the bending machine can be relieved. A constantly high buffer occupancy is counteracted. However, rearrangements highly affect both, the fulfillment process of all nested orders, and the situation in the sorting area. Other objectives in the production should not be impaired. As the effectiveness of such an approach is not obvious, and it is the simplest approach to integrate, as it does not affect the production organization, this rescheduling

option is further observed in section IV and validated in a process simulation (section V).

IV. Methodology for Rearranging Sheet Programs

The *rearrangement of sheet programs* aims to optimize the production flow, when b_{target} is exceeded. For this, a further production of sheet metal parts, that require a bending process, should be avoided. Nevertheless, planning in sheet metal works focuses on machines, as well as on material utilization. For this, the laser cutting machine constantly continues producing sheet metals that include different parts of various nested orders. A valid rearrangement of the sheets in the production schedule is aimed to be found, avoiding the postponement of any urgent orders, as well as restricting to pull apart the production of individual parts of an order over a long period of time.

The proposed algorithm (see Algorithm 1) consists of three steps. It sets in every fifth sheet and calculates a possible rearrangement of the ten sheets $\langle s_i \rangle_{i=1,\dots,10}$ subsequent to the freeze zone. This interval gives the production planner enough time to decide if the proposed rescheduling should be implemented or not.

1. **Optimization target:** The optimal sheet sequence according to the sole optimization objective of relieving the bending process is determined. For every sheet, the total number of bending operations α_{s_i} is calculated by adding the number of bending operations of every nested part. The sheets are sorted by an ascending α_{s_i} and form the *bending ranking*.
2. **Constraint elaboration:** For every order o_j, its priority is updated constantly. It results from the current interval to the planned execution or delivery time. Here, a binary priority is assumed. In case of a high priority, the execution of the order should not be postponed, if the parts are the last parts of its order in the production plan. This means a sheet containing such an order cannot be rearranged to a higher position in the sequence. Its *last possible position* β_{s_i} is the original position. In case of a low priority, the sheet might be pushed backwards by a defined *movement parameter* λ (e.g. λ = 4) to β_{s_i}.
3. **Iterative sheet rearrangement:** The sheet sequence is optimized according to the *bending ranking* under compliance of the *last possible position* of each sheet.

The algorithm puts out a new proposition $\langle u_i \rangle_{10}$ for the sheet program sequence. The human production planner is asked, whether the proposition is accepted or not. This measurement is taken to achieve the acceptance of the system in the introduction phase and might be switched off. In case of an approval, the five upper sheets are pushed into the freeze zone for cutting, the remaining sheets might be introduced into the algorithm again. If λ is smaller than the execution interval, a continuous postponement of sheets is avoided.

```
input : copy of 10 sheet programs ⟨s_i⟩_{i=1,...,10}
        including nested orders O_{s_i}
output: rearranged sheet sequence ⟨u_i⟩_{i=1,...,10}

for each s_i ∈ ⟨s_i⟩_{i=1,...,10} do
  | calculate sum of implied bending operations α_{s_i}
sort ⟨s_i⟩_{i=1,...,10} by ascending α_{s_i}
result: bending ranking ⟨t_i⟩_{i=1,...,10}

for each original s_i ∈ ⟨s_i⟩_{i=1,...,10} do
  | s_i's last possible position β_{s_i} = 10
  | for each order o_j ∈ O_{s_i} do
  |   | if o_j's last part's sheet position γ_{o_j} < β_{s_i}
  |   |  then
  |   |   | if o_j's priority is low and
  |   |   |  γ_{o_j} + movem. param. λ < β_{s_i} then
  |   |   |   | β_{s_i} = γ_{o_j} + λ
  |   |   | else
  |   |   |   | β_{s_i} = γ_{o_j}
  |   | else
  |   |   | return
result: sheets' last possible positions inside the
  sequence S = (s_i, β_{s_i})_{i=1,...,10}

sort ⟨s_i⟩_{i=1,...,10} (iteratively) according to ⟨t_i⟩_{i=1..10}
  by strictly complying to the constraints β_{s_i}
result: rescheduling proposition sequence ⟨u_i⟩_{i=1..10}
```

Algorithm 1: Rearrangement of sheet programs

V. Application and Results

A. Simulation process

The simulation of the production process consists of the following steps (compare to Fig. 2.):

1. Order creation and sheet metal nesting
2. Dispatching into freeze zone
3. Laser cutting process
4. Removing, sorting and post processing
5. Waiting period in bending buffer
6. Bending process
7. Optional: hot jobs / rescheduling

The input for the process simulation are m generated orders, which contain the randomly created information, whether a bending process is required as well as a random forecast of the bending lead time. For each order, a due time according to the sequence of the generated orders is determined, based on a standardized interval, which corresponds to the rough planning done by ERP-systems. The sheet metal nesting process generates n sheet programs by assigning all parts of the generated orders onto the sheets. The orders are queried in an ascending order, based on a defined probability parameter, until each part of every order is nested onto a sheet. It is determined, how many orders are nested onto a sheet, for which, a randomized cutting lead time is set. Periodically, a defined number of sheets (here 5) is pushed into the freeze zone, where they are processed successively

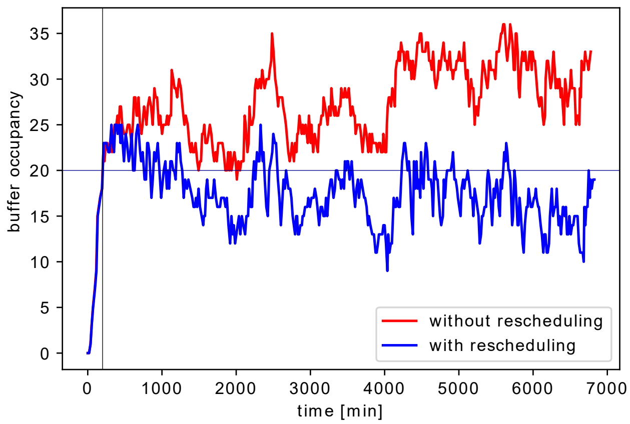

Fig. 3. Buffer occupancy over time - *1 sample, 2000 sheets, 5 nested orders*

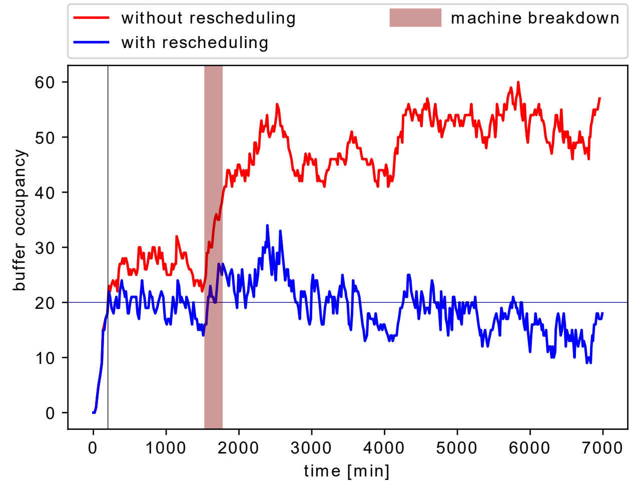

Fig. 4. Buffer occupancy over time including machine breakdown

by the cutting machine. Next, the cut parts go through the sorting area, where they are removed from the sheet, sorted, and post-processed, until all parts of an order are finished. Orders without bending are directly pushed into the storage for delivery. Else, the bending parts are moved into the bending buffer area, where they are randomly picked by the workers for bending. Hot jobs are introduced randomly into the process. The control variable of the rescheduling algorithm is the buffer occupancy. Selected parameters in the simulation are based on average values. All process steps are logged and evaluated.

B. Simulation results

Various conclusions can be derived from the simulation results, out of which some will be presented here. For all presented results, b_{target} was set to 20 orders. The rescheduling, triggered by exceeding b_{target}, aims for pushing the number of orders slightly below it. In practice, the buffer occupancy should not become too small, as the workers need to be able to pick out of a selection of orders for minimizing set-up processes.

The main optimization parameter of the concept is the buffer occupancy. Fig. 3. illustrates the effect of the rescheduling for a sample of orders. To generate the initial situation, the bending machines do not start to produce, until the buffer occupancy exceeds 20. It can be seen, that the buffer is subject to high deviations despite the assumption of constant machine productivities. The application of the rescheduling limits a further growing intermediate stock. Fig. 4. shows an even more remarkable effect, as a breakdown of one of the bending machines over four hours is assumed. Without the rescheduling, the bending buffer increases significantly, whereas the application of the rescheduling can balance the effect of the breakdown after a certain amount of time.

Interestingly, even for a higher number of nested orders, the rescheduling holds a very positive effect, although the limiting constraints for the sheet rearrangement increase. The rescheduling pushes back single sheets in the scheduling sequence by the small movement parameter λ only, dependent of the priority of the nested orders. For this, a more minor effect might be expected. Fig. 5. illustrates the effects on the due times of ordinary bending orders as well as on hot jobs. One drawback of the sheet metal rearrangement is the temporal stretching of the cutting process of orders, which results in an increase of incomplete orders located in the sorting area. However, the average bending buffer occupancy highly decreases. The respective increase at the sorting area is much smaller (see Fig. 6). Additionally, the removing, sorting and post-processing are not bottleneck operations and do not require special operator skills.

VI. DISCUSSION

The concept for an event-driven production rescheduling holds great potentials as it assumes the right abstractions to create a universally applicable solution that highly optimizes the production process without impairing other optimization objectives. Finding a global optimum is desirable, but is hard to achieve as explained in the paper. The comparison of the

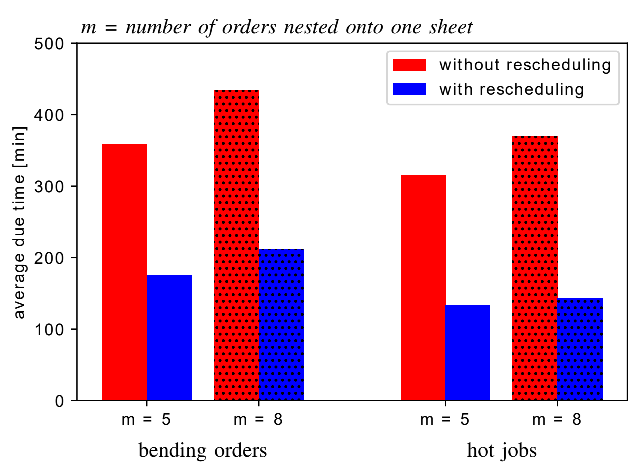

Fig. 5. Average due times - *20 samples, each 2000 sheets*

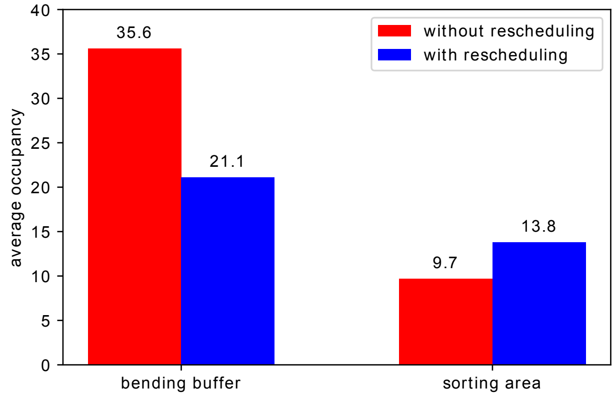

Fig. 6. Average buffer occupancies - *20 samples, each 2000 sheets*

results to the global optimum is not possible, as this optimum remains unknown due to the high implication of human actions in the system. The concept assumes a b_{target} of 20 orders, which is estimated arbitrarily and is highly dependent on the real production environment. In practice, b_{target} should be lowered progressively until a factory-individual optimum is found, considering the required buffer occupancy for set-up optimization as well as the effectiveness of the algorithm dependent of the production process deviations. At best, the buffer occupancy oscillates around b_{target}. The application of the concept in terms of a simulation with original production data is not meaningful, as all processes on the shop-floor are interdependent and are influenced by human actions. For this, randomly generated data is used. The simulation aims for drawing fundamental conclusions about the evolution of the bending buffer occupancy and assumes various neglects and abstractions. A realistic simulation is hard to achieve, but should to be approached incrementally for further investigations. For instance, the order picking inside the simulation, as well as the set-up process at the bending machine display the real process imprecisely.

VII. CONCLUSION AND FUTURE WORKS

This paper presents an event-based approach for rescheduling sheet metal productions to improve the order flow on the shop-floor. Choosing the occupancy of the buffer at the bottleneck operation as a control parameter proves to be an effective and easily measurable way of aggregating the different kinds of production deviations from the predicted schedule. Furthermore, the buffer occupancy turns out to be a good optimization objective as a meta parameter for various kind of optimization KPIs, leading to decreasing lead times and intermediate stocks, as well as to a much higher predictability of delivery times. It introduces production pull aspects into the process. Three different approaches are presented, from which the *rearrangement of sheet programs* is observed in a production simulation, showing the highly positive effects of the concept.

The usage of ERP-, MES-, PPC- and/or APS-systems at different metal works is very diverse. The proposed rescheduling approach is strictly distinguished from the surrounding IT systems and can easily be implemented in different IT infrastructures without the need for complicated modifications, acting as a complementary to applied predictive scheduling systems.

The concept is valid for every kind of sheet metal job shop, aiming for abstractions of the complex problem. The production process is optimized without impairing other optimization objectives. The calculation of the rescheduling proposition highly relies on the respective order priorities, which leads to a more and more order-centered planning. The priority calculation might be further observed, especially for production processes containing a component assembly as a further production step.

In the future, an integration of the nesting process might be approached as it holds high potentials. However, this is a very complex task, that has not been solved so far and carries the risk of sub-optimization.

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