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BACKWARD SIMULATION: A CUSTOMER-FOCUSED DIVERSIFICATION OF FAB SIMULATION APPLICATIONS IN A HIGHLY AUTOMATED SEMICONDUCTOR PRODUCTION LINE

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ABSTRACT

In modern manufacturing environments, the digital transformation to smart factories cannot be achieved without data-driven methods like discrete, event-driven simulation. This paper provides an overview of existing current simulation applications at Infineon Dresden in this area, especially on short-term simulation for production control and long-term simulations to forecast process flows in the wafer fabrication facilities. Furthermore, it illustrates the current status of research activities in the area of backward simulation for operational decision support for order scheduling by some latest research results.

1 MOTIVATION

In all kinds of manufacturing environments, the digital transformation to smart, changeable factories cannot be achieved without data-driven methods and analytical tools; their comprehensive and consistent implementation creates the best conditions for the planning, realization ramp-up and operation of modern, competitive factories. Moreover, companies need to be constantly aware of the continuous adoption screws in production planning and control (PPC) in order to establish and maintain the best-possible "optimal operating state" and therefore an efficient organization of all manufacturing processes. Uncertainty in PPC and the resulting adjustments can have unexpected repercussions on the performance of production systems and result in monetary and time resources being misused. A permanent (effective) adjustment of PPC also requires flexibility regarding structuring within manufacturing companies to be able to adapt to continuously changing market situations and correlating customer requirements. In operations, planners and decision makers are faced more or less daily with the challenge of achieving fixed production programs and subsequently individual orders in a certain quantity and within a certain period at a guaranteed completion date. The success in terms of an efficient flow of manufacturing goods demand systematic approaches for, planning, scheduling, and tracking of resource requirements.

Discrete event-based simulation (DES) can not only be used as a planning tool for strategic and tactical system design and its safeguarding under uncertainties; it can also be applied as an operational decision support tool. DES-applications can provide decision-makers with insights into how a system will behave under different scenarios, allowing them to make informed decisions about how to optimize the system's performance. DES can be used to simulate the effects of different scheduling policies, equipment configurations, and maintenance schedules for an existing manufacturing system and allow a simulation-based forecasting by the execution of simulation experiments, initialized with the factory's actual WIP (nowadays known/marketed as Digital Manufacturing Twins). This can help to identify bottlenecks and inefficiencies in the actual production process and allow managers to adjust in order to improve productivity, reduce costs, and increase throughput (for some examples see Ferro et al. (2017) or Kasie et al. (2017)). This paper focuses on multiple practical and simulation-driven approaches of Infineon Dresden (IFD) in this field, which are part of the business processes today as well as latest research, carried out by a cooperation with the research group Industry Analytics of the University of Applied Sciences in Zwickau (both Germany).

IFD produces customer-specific logic chips in high-automated 200mm and 300mm semiconductor fabs in Dresden. Conflicting goals have to be mastered, short product cycle time, fast development cycles and a high utilization of the production line for an efficient operating have to be ensured. At facility transitions lots are stored and continuation of the lots is triggered by customer order to the supply chain. These facts substantiate the need for simulation methods on all levels of the production process. The widespread application area covers the short-term lot arrival and WIP forecast for production control issues and the long-term performance forecast for dynamic capacity planning. If the focus is set on downstream facilities, e.g., Wafer Test and Pre-assembly, the delivery reliability for every individual lot is even more important.

As a part of IFD's latest research activities in this field, a specific backward simulation approach has been carried out in the last years, to allow an improved controlling of lot delivery dates by optimization of lot start pattern. As some of the research activities already have been published (e.g., Laroque et al. 2021; Laroque et al. 2022), in the later sections some latest results will be described to update on these activities and roll-out the path for future work till a working prototype is applied by the end-users at IFD as a simulation-based decision support tool.

2 FAB SIMULATION IN DAILY IFD-BUSINESS

High complexity, caused by the variety of technologies and products with approximately 400 up to 1000 steps and with a lot of reentrant process flows in the wafer fabrication facilities, has to be mastered ensuring short product cycle times and fast learning cycles for product development. An accurate material forecast for better planning and execution is required synchronizing material flows from one facility to another (Scholl et al. 2018). In upstream facilities the continuation of the lots is triggered by customer order to the supply chain. On the other hand, a high utilization of the more than 1000 expensive machines is needed for a profitable manufacturing. In daily business overall equipment effectiveness analysis (OEE) are necessary to find out capacity gaps. Enhanced static capacity planning method with pre-defined capacity load limits, based on operating curve analysis and intelligent solver solution for an optimized equipment utilization, is also an important component, but can't cover all of the dynamic effects in a semiconductor production line. For this reason, at Infineon Dresden the discrete-event fab simulation with the commercial software AutoSched AP from Applied Materials has been established to a frequently used decision-making method. All simulation applications run on a standard desktop workstation. Steady-state approach is mainly used for assessment of future capacity ramp scenarios and validation of dispatch rules. More important is the transient simulation, initialized with actual line situation and resulting in a forecast of time-dependent trends for all important performance indicators. The widespread application area covers the short-term lot arrival and WIP forecast on level work center (Scholl et al. 2011) and the long-term performance forecast on level Fab, work center and product with a 6-months-horizon. Specific modeling approaches are needed to cover the widespread application area from planning to operations. We don't use one master model; different applications mean different modeling approaches.

2.1 Short-Term Simulation for Production Control Decision Support

Typical questions in operations are answered by short-term simulation, e.g., what is the best day to start a preventive maintenance activity and a bottleneck early-warning including root cause analysis (Scholl et al. 2012). Due dates of wafer-counter based maintenance activities can be forecasted, e.g. in sputtering area. Based on live data factory information early-warnings are automatically sent to affected production departments, if needed resources (e.g. probe cards in Wafer Test area) are not available.

This 7-days forecast is based on a highly detailed simulation approach of the material flows and is considering all routes, sampling procedures at measurement and inspection steps, all actual dedications and accurate modeling of logistical constraints, e.g. time-linked steps. Basis for this daily updated, highly automated application is a complex architecture with link to more than 30 data sources realized with an SQL interface and APF Formatter from Applied Materials (Figure 1).

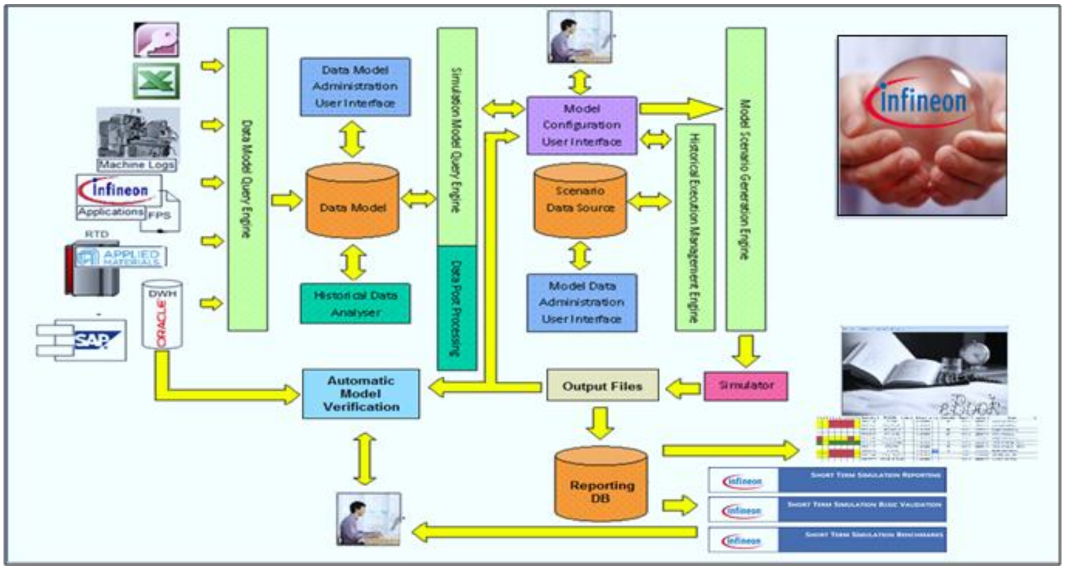

Figure 1: Short-term simulation architecture (conceptual scheme).

Key results are a 7-day lot arrival and WIP forecast for all work centers (Figure 2). The last 3-days of historical data are displayed for a fast plausibility check. Simulation results are translated into a qualitative statement (green/yellow/red ranges) to improve the usability for the customer from production departments.

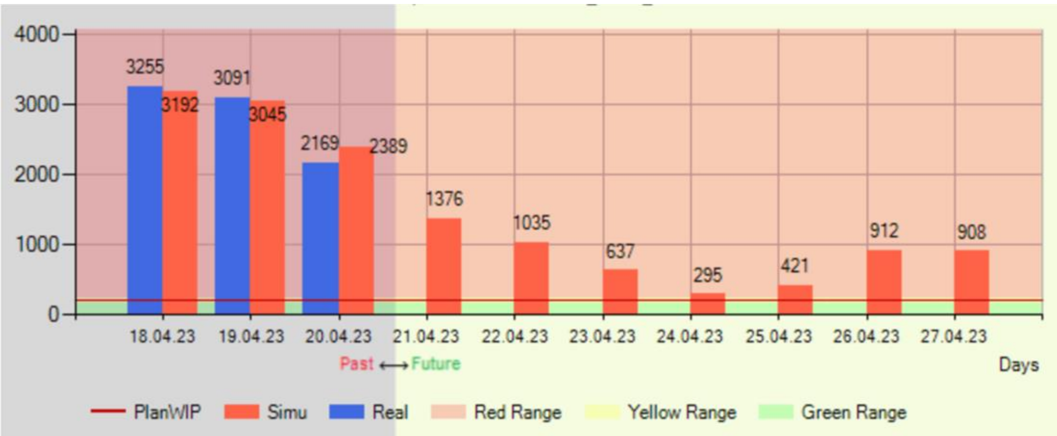

Figure 2: 7-days WIP forecast including historical data and qualitative statement.

Root-cause analysis in case of forecasted bottleneck situations is supported by a drill-down functionality. For example, the lot arrival streams can be displayed on granularity upstream work centers (Figure 3).

This application is very sensitive to input data quality and exactness of information about future machine and process availabilities. Integrated data validation and functional check procedures are required.

This system was developed together with D-SIMLAB Technologies and supports expert driven simulation model administration, automatic model correction and verification (D-SIMLAB Technologies 2018).

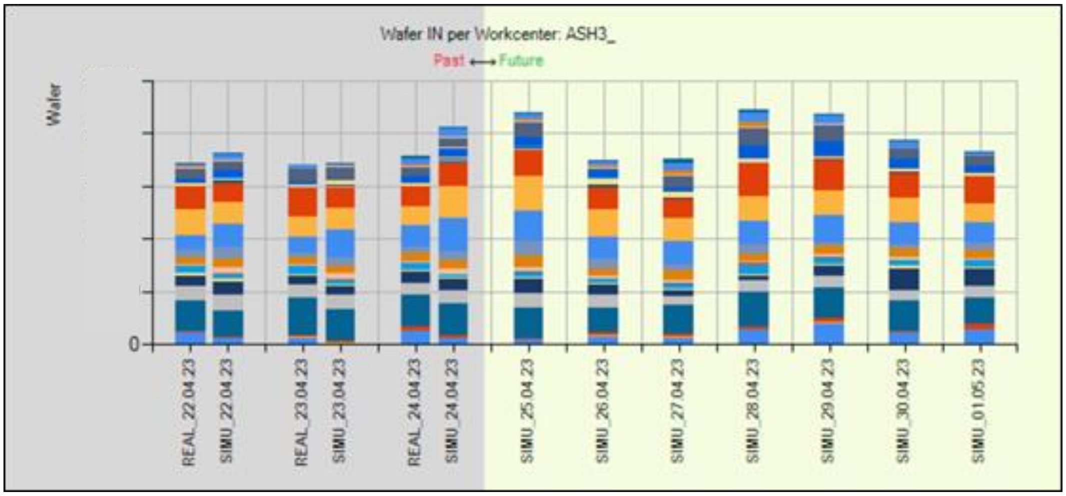

Figure 3: Arrival forecast with detailed incoming stream analysis.

2.2 Long-Term Simulation

High variety of technologies means a mix of material flows with 200 to more than 1000 steps and with a lot of reentrant process flows in the wafer fabrication facilities. Especially in overload situation, a time-delayed reaction of performance indicators after line incidents is a typical behavior, that also means recovery time of several months after line incidents are often observed, sometimes unexpected amplification effects, too. The dynamic long-term Fab behavior is unpredictable with static planning methods or the usual operating curve approach only (Figure 4).

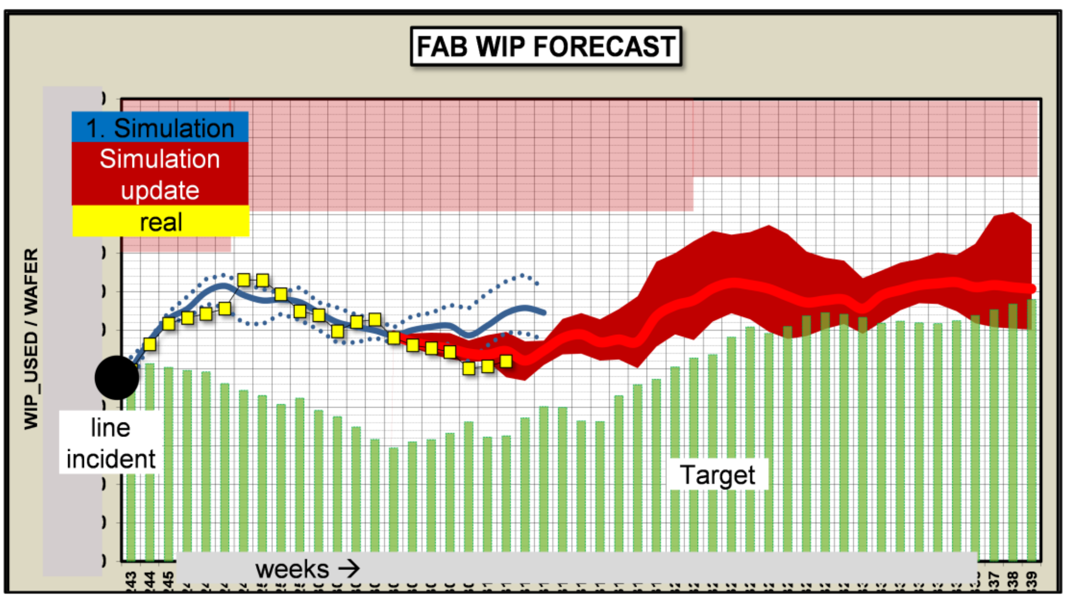

Figure 4: Long-term WIP forecast after line-incident (forecast and real).

Main application of long-term simulation is the 6-months-forecast of all important key performance indicators (e.g., cycle time, WIP, wafer out) on a higher aggregated level (fab, product group and work center) compared to our short-term simulation. The quarterly updated forecast is used for definition of financial and production targets for the next 6 months. In addition to this strategic application the long-term simulation runs weekly based on updated customer demands, current work center uptime and e.g. scheduled production interruptions to quantify the performance impact, partially resulting in a finetuning of wafer start plan. A wide variety of production and Fab loading scenarios are evaluated by long-term simulation. Very important is the dynamic evaluation of planned additional wafer starts or lot prioritization concerning positive delivery effect compared with expectation and the negative side-effect on product cycle time (Scholl et al. 2018). Major changes in dispatching and product prioritizations are also triggered by fab simulation. High focus is on a customer-friendly visualization of the results. As an example, the forecast of expected WIP-waves and its visualization after a local bottleneck situation can be derived (cp. figure 5 (purple color indicate a high-volume over time and process steps)).

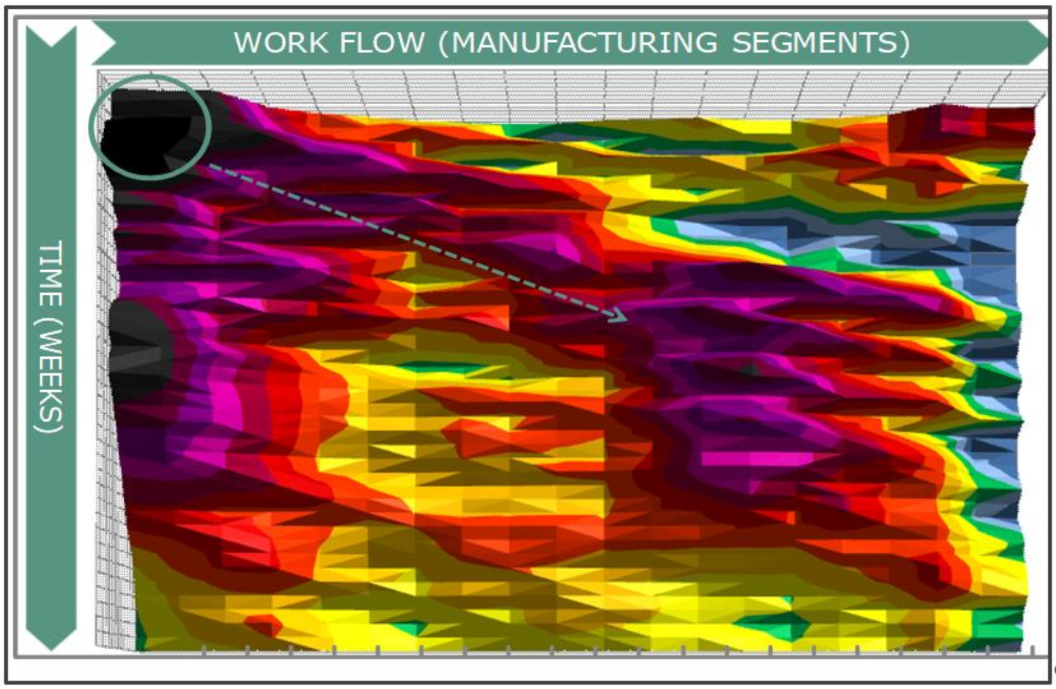

Figure 5: Long-term effect of a temporary bottleneck on WIP profile.

In contrast to the highly detailed short-term simulation model the long-term simulation based on a more simplified approach. That means, fab modeling on higher aggregated level with strong focus on transparency and robustness especially to pseudo-accurate future information and basic data quality. Deterministic modeling features, e.g. sampling procedures and preventive maintenance plans are replaced by stochastic approaches. Reduced data volume makes it easier usable for a wide range of applications and what-if-scenarios. Of course, model simplification requires a continuous validation process to ensure high forecast accuracy on needed information level. The simulation results are derived from 10 confidence runs. Based on our longtime experience, this is a reasonable compromise between accuracy and runtime (typical in the range of 8…15 hours).

3 SIMBACK-APPROACH FOR OPERATIONAL DECISION SUPPORT

3.1 Motivation from the Industrial Perspective

In addition to the given examples, where Infineon Dresden commonly uses fab simulation approaches in order to support the operational planning process, we have developed a discrete event-oriented fab simulation model where decision and planning problems are based on a backward directed termination. This approach is called backward simulation and means the inversion of the material flow in the model including execution logic. Customer due dates are used as lot release time into the fab simulation model. The lots then flow through their inversed product's route sequence until they finish the last step. The resulting lot completion time is used in the forward directed simulation as latest start time when it needs to be started so that it can meet the customer due date in time. By knowing a valid "latest start" time of a specific order/lot in such complex environments, operational production planning and control may ensure the completion of most of the orders in-time and nevertheless have a maximum flexibility for their order sequencing till that point in time. Short-term changes can be allowed as long as a on-time delivery is ensured. Motivation for this approach is the focus in downstream facilities, e.g. Wafer Test and Pre-assembly, on delivery reliability for every individual lot. Fortunately, from the view of feasibility, the characteristic of these facilities is a flow-line production without reentrant process flows, batching and time-linked steps. An additional challenge arises, that lots have to be started from stock on facility interface. An early-warning system is needed, if there is not enough inventory to fulfill the order from costumer or supply chain in due time.

3.2 Backward-Oriented Planning by DES

Scheduling is a continuous decision-making process that involves scheduling tasks over time periods. The goal is generally to optimize one or more objectives. This can be used in manufacturing as well as other industries where demand changes almost daily (Pinedo 2016). The procedures of a forward and backward scheduling can be distinguished, which serve as solution procedures for scheduling and the correlating scheduling logic. Typically, scheduling steps often include assigning times, establishing priorities (priority control), prioritizing resources from highest to lowest priority and tracking progress towards completion, among others (Dangelmaier and Warnecke 1997).

Whereas forward scheduling is a process that sets deadlines for each work task and moves from a certain starting point (date) to complete the work within a specified period, the focused backward scheduling approach determines the latest possible start date of individual orders based on pending completion dates, which is especially useful for scheduling all kind of orders promised to customers with guaranteed completion dates. The approach offers an advantage in flexibility within PPC, since given orders are not manufactured until the latest possible date, so that changes in configuration, due dates, lot sizes among others can be adopted for a longer time period.

In addition to existing approaches based on mixed integer optimization, simulation-based heuristics, and simple forward or backward scheduling, simulation-based optimization is becoming more important in manufacturing, see Block et al. (2017) and Lendermann et al. (2020). Gutenschwager et al. (2017). Since existing methods of mixed integer optimization often use only rather simple models to keep computation time within reasonable limits, discrete event-oriented simulation (DES) can handle much more complex models. DES models are used individually or in combination with heuristics in the context of simulation-based optimization to study forward-time decision and planning problems. The described approach of discrete event-oriented simulation with respect to time-backward decision and planning problems has been described in the literature as backward simulation and concretizes a reversal of the flow logic of the simulation along with the implemented control and priority rule procedures and the resulting backward execution of the same. According to Jain and Chan (1997) (among others), a backward simulation can be used to make well-founded statements about the target values to be achieved in the context of promised delivery dates. Furthermore, backward simulation is an efficient tool for implementing the procedures of (simple) backward scheduling, whereby both the solution quality of a conventional production planning and scheduling mechanism and the execution speed of simulation-based scheduling approaches become effective. In most applications, the validation of the resulting solution set is carried out by a follow-up of a forward simulation. Such a combination of a backward and (validating) forward simulation is understood as SimBack. As Leißau and Laroque (2023) shows, multiple other applications of backward-oriented approaches have been carried out in the past.

3.3 Latest Results

Derived from the existing previous work, the authors have now focused specifically on the change in lot sequence at the beginning and end of the process section under consideration and in between at individual operating steps. The considered model of the pre-assembly process essentially consists of 13 station groups with up to 27 stations per station group and an available capacity of up to 8 lots per station. An additional station group DUMMY is a strong abstraction of the reality to be represented and, in relation to the number of identical plants, an exception (number of stations = 1000); it was chosen to avoid artificially created bottlenecks in the simulation of the material flow. Earlier explanations and experimental results can be found in Laroque et al. (2022). Figure 6 shows the deviation of the lot sequence over the process steps in the simulation model. Red lines indicate a deviation in the arrival date compared to their specific deadline in the forward simulation approach.

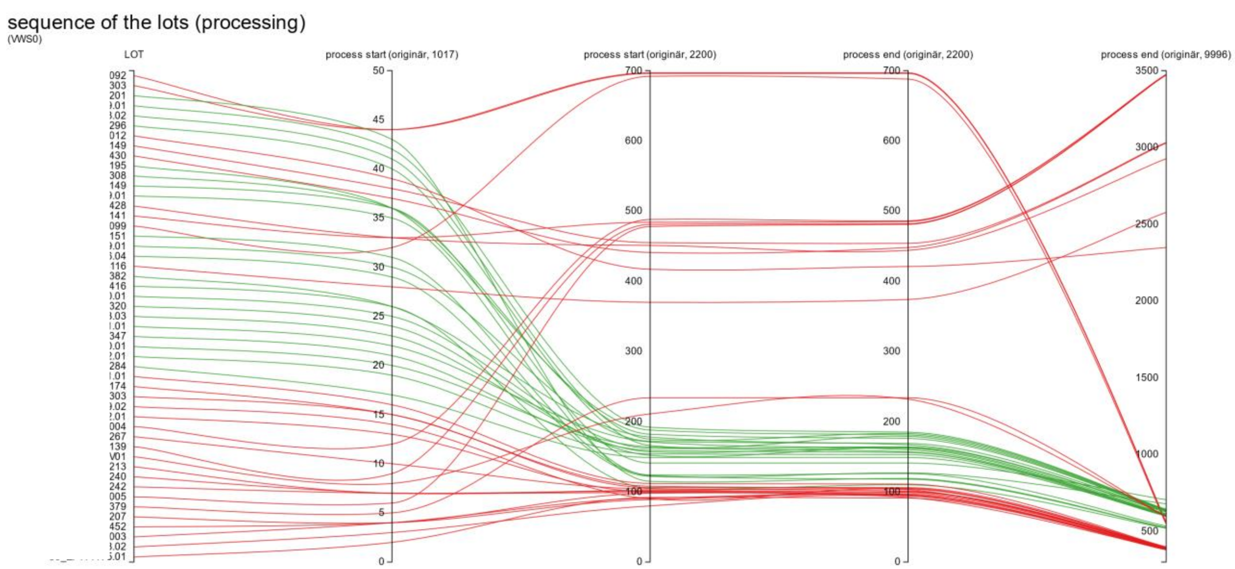

Figure 6: Lot sequence from initial simulation run (VWS0).

In the following, the consideration of the lot sequence refers to the original (forward) simulation (VWS0) and results subsequently of the backward simulation in terms of a combined execution. The authors consider in each case 50 consecutive lots after original scheduling and show the change of the lot sequence over the individual operations.

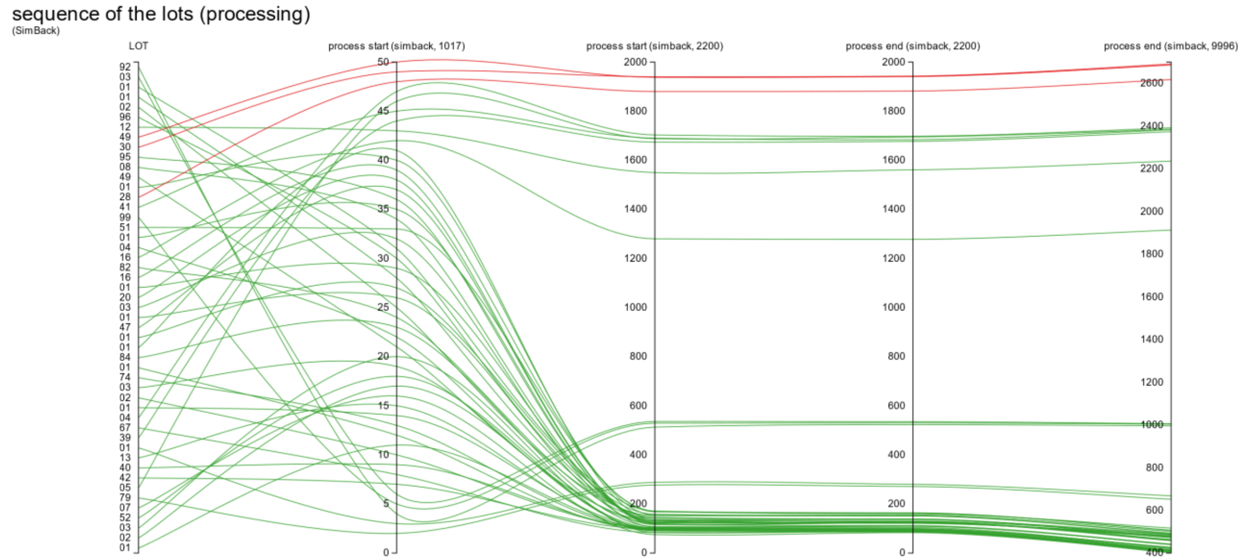

Figure 7: Lot sequence resulting from SimBack planning.

Exemplarily, figures 6 and 7 show the lot sequence at the beginning and at the end of the considered pre-assembly process, where in addition another operation step has been selected within the routings. The results show that most of the lots in the backward simulation are completed on time within a time window of ±72 hours compared to the original simulation. Accordingly, in the original simulation only 21 out of 50 lots can be completed on time, while in the backward simulation this refers to 47 out of 50 lots (indicated by a higher amount of green lines in figure 7 compared to figure 6). On-time lots are labelled in the figures by green markings, unpunctual lots are coloured red.

4 SUMMARY AND OUTLOOK

This paper provides an overview of existing current applications of IFD in the area of material flow simulation and describes the current status of research activities in the area of backward simulation for operational decision support for order scheduling. The SimBack approaches serves as a backward-terminating planning approach; its results are validated by a forward simulation of the resulting lot sequence and can be compared in a real-world scenario with existing approaches and their historical production data. Without further optimization of lot sizes, sequences and the shifting of due dates, the backward simulation approach is able to provide a lot schedule, that serves the overall goals of production planning and control.

The current applications, which are already operationally in use today, will be successively further developed and, where necessary, modernized depending on the specific requirements of the end users.

In the area of backward simulation, a joint research project started in July 2023, where the existing research results will be underpinned by new use cases and continued to an applicable prototype. It will consist of more sophisticated approaches regarding the optimization of the lot schedule by the use of larger-scaled simulation experiments (Data-Farming) and a procedure to knowledge extraction from this generated simulation data. The continuous practical development and application on a real-world example of the concrete factory in Dresden will help to work out in particular also limits of the method employment.

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