Automated and Optimized Lot-To-Order Matching in 300 mm Semiconductor Facilities

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Abstract—Lot-to-order matching (LTOM) is considered a critical step in the manufacturing process as an inefficient allocation has substantial adverse impacts on fab performance. Several optimization approaches have been developed in research, but successful use cases and best practices are scarce, particularly for 300 mm semiconductor facilities. Our contribution addresses this insufficiency and presents the approach and results of an automation and optimization project for the LTOM process of 300 mm production lines at Infineon Technologies Dresden and Austria. Within our approach, we first analyzed and standardized the former manual as-is process using the Business Process Model and Notation approach to enable it for automation before we focused on further targeted optimization of the process and the developed IT artifact. The results led to considerable positive effects on essential qualitative and quantitative KPIs, such as delivery reliability, throughput, customer satisfaction, and workload reduction. Furthermore, we describe challenges that occurred during the project and present applied measures.

Keywords—lot-to-order matching, case study, factory automation, semiconductor manufacturing

I. INTRODUCTION

Considering Moore’s law, semiconductor companies usually pursue the “More-Moore” strategy, i.e. output maximization for a limited number of products. In contrast, our case company Infineon Technologies Dresden (IFD) follows the “More-than-Moore” strategy, i.e. broader diversification through higher product variety [1]. Therefore, IFD has implemented the first worldwide production line of power semiconductors on 300 mm (12″) wafers, which runs on an even higher product mix than its 200 mm (8″) equivalent. For semiconductor manufacturing facilities, the allocation of supply and demand is both a strategic and an operational decision. This paper focuses on the operational decision, referred to as lot-to-order matching (LTOM), which is applied at the die bank area of the fab [2]. The die bank constitutes the order decoupling point where the production mode changes from make-to-stock to make-to-order. Thereby, wafer lots are assigned to affirmed customer orders. The problem was introduced as an integer programming problem by Knutson et al. [2]. The authors aimed at maximization of tool utilization and on-time delivery (OTD) while at the same time reducing excess products and inventory. In the common LTOM formulations, an underallocation of wafers is not allowed, and a single wafer cannot be split between orders. Inefficient allocation leads to overproduction as semiconductor manufacturers seek to fulfill all approved orders [3]. Thus, the LTOM process directly affects essential KPIs, such as profitability, OTD, throughput, and the distribution of lots and physical operations (lot splits), i.e. tool and transport system utilization [4].

The existing scientific literature on the topic is detailed next. After the decomposition heuristic was presented by [2], heuristic methods were used in [4] for a two-stage formulation that involves factory allocation as a knapsack problem and LTOM as a bin-covering problem. In a related article [5], the authors developed variants of first-fit-decreasing heuristics to solve the problem stages. In [6], the class-constrained lot-to-order matching problem was decomposed into two steps: (1) a decision on which customer orders to fill; and (2) the assignment of specific lots to chosen orders. The authors developed a first-fit decreasing heuristic with an improved endgame that performed well to maximize OTD and die of customer orders while total weighted tardiness and excess die were minimized. In [7], uncertain lot-sizes were considered in a generalized lot allocation problem and solved with robust optimization models that offer certain flexibility as input data might be uncertain. Focusing on a combinatorial optimization problem with the objectives of minimized backorder and tardiness penalties as well as product downgrade and excess costs, [8] examined several heuristics and indicated the superiority of their developed composite allocation rule. Recently, [3] studied LTOM at semiconductor backend facilities as a bin covering problem again. The authors proposed a multi-start swap algorithm, where for multiple initial solutions, wafers are exchanged in swap moves to minimize cumulative overallocation.

To sum up the existing literature, there has been considerable research effort to develop heuristics that perform well for different problem formulations. However, empirical investigations and the incorporation of real-world specifics are scarce. Therefore, we conducted an exploratory and longitudinal in-depth case study [9] and contribute with the results, challenges, and lessons learned of a research project to...
optimize and automate the LTOM process in two power semiconductor manufacturing fabs. In our holistic approach, we opt against the mere heuristic optimization of the problem, as numerous constraints influenced the process under investigation. Instead of static optimization, our procedure relies on rule-based, continuous optimization and automation in real-time and is described in detail in the following section.

II. CASE STUDY

At the beginning of the project in 2018, fabrication and testing of 300 mm wafers at IFD were already nearly fully automated. However, the associated LTOM process remained mostly manual. Human operators in the Line Control (LC) department need to ensure delivery reliability by simultaneously handling hundreds of different products. Therefore, the employees had to assign lots and start dates manually, which led to uneven and peaked sectioning of lot splits and lot start quantities in the fab. A fixed weekly key date for data transfer impeded the requirement to react flexibly to delayed lots and varying customer due dates. Additionally, both the personnel workload and error susceptibility increased with the further ramp-up of the 300 mm line and the continuous launch of new products. To counteract this development, IFD had to automate and optimize the LTOM process inevitably. That was done within a research project and consortium of leading semiconductor companies.

The project goals included continuous and uniform sectioning, equally distributed lot splits and quantities, as well as an automatic lot assignment and start date allocation. The target process should enable higher flexibility, working time savings, and employee effort shifts to more creative and valuable tasks. The solution was also meant to be transferred to the 200 mm manufacturing line of IFD and other fabs, i.e. Infineon Technologies Austria (IFAT). In sum, the research goal was to develop and implement a holistic, inter-organizational, and future-oriented approach for the LTOM process of different sites. Therefore, the project was divided into two main phases: (1) enabling and automation; and (2) further optimization. We applied this sequence due to the involvement of various stakeholders and the expected time-consuming consideration of all requirements. Thus, the existing business process was first automated to offer an initial solution that provided quick wins, i.e. increase employee acceptance and economic justification. Subsequently, we focused on the further alignment and optimization of the automated workflow, extensive process landscape, underlying IT architecture, and additional requirements of the fabs.

The project involved several stakeholders (i.e. both staff and managers) from IFD and IFAT, including departments like LC, production planning, information technology (IT), wafer test, simulation, and manufacturing. Between 2018 and 2021, we collected rich primary and secondary data using multiple “sources of evidence” [9]: documentation (i.e. internal reports and charts, e-mails, and process descriptions); archival records (i.e. organizational records, websites, and research publications); direct observation (i.e. site visits, project workshops, and weekly meetings with the various stakeholders); employee observations and unstructured expert interviews as part of the business process modeling process and user experience evaluation; and physical artifacts (i.e. several newly developed or enhanced IT systems and tools). We explain the two phases of the project in the following.

A. Phase 1: Enabling and automation

In the first step, the as-is process was analyzed and modeled using the well-established Business Process Model and Notation (BPMN 2.0) [10]. The initial workflow was characterized by matching lots to orders manually. The LC staff processed a list of orders in an MS Access database, where the available lots for each order were displayed on demand. However, only the most relevant information was included, i.e. product type, wafer count in the lot, and time passed since arrival in the die bank area. During the manual allocation of the orders, the employees had to consider four different objectives: (1) an efficient allocation (preferably lots that exactly match the requested wafer amount) with few resulting lot splits; (2) the feasibility and availability of lots (i.e. readability, ability to split (“unzip”) and merge (“zip”), actual hold codes, and exceptional lot related stops); (3) the age of the lots, as various products are stored in the die bank under nitrogen and are susceptible to age-related efficiency losses (therefore, older lots should be assigned preferably); and (4) the use of residual lots to free up storage space which in turn leads to an increased load of the transport system and should therefore be balanced. Regarding the sequence of orders assigned, the production planners use a job priority flag to assign a priority status, resulting in a preferred assignment if recognized by the LC staff. However, this manual process is prone to error and the consideration of job priority flags require their correct assignment according to comment agreement rules, which is not always the case.

The start dates were allocated to each lot, determining the release date for the next production stage. Further tasks included the specification and scheduling of lot splits and capacity checks. The distributions of the released lots and splits across the available periods were irregular as all dates had to be typed in by hand, resulting in a fluctuating tool and capacity utilization. The weekly lot start plan was generated by LC and sent to affected stakeholders via mailing lists. Required updates entailed high efforts for work and communication. Process flexibility was further limited by a fixed weekly date for data transfer from upstream IT systems and rigid deadlines for permitted allocation modifications. The fixed weekly date also led to an underutilization of capacity for this day as LC staff was caught up in manual data transfer, data checks, LTOM, and start date allocations for the upcoming week. Multiple redundant feedback loops prevented a seamless workflow and increased communication efforts and error-proneness. Regularly, the LC staff had to reschedule as production planning pushed for prioritized lot starts or change of lot status to “hot” or “rocket”, leading to WIP fluctuations and non-optimal processing sequences.

Due to the influencing factors mentioned above, the standardization of the as-is process was crucial and addressed during the modeling procedure using BPMN 2.0 [10]. Thereafter, we collected the requirements of the various process stakeholders, assigned them to either Phase 1 or Phase 2, and derived an aligned target process. This procedure enabled us to realize apparent optimization potentials already within the first phase. The deduced to-be process facilitated the automation of the following tasks: lot-to-order assignment, lot start date allocation, lot splits, and operational capacity checks. Moreover, uniform day-and-night lot starts as well as equally distributed lots, splits, and quantities were targeted for a steady line utilization. We defined subtasks, assigned clear task responsibilities, and implemented various weekly job fixes involving the affected stakeholders. As a result, we
prepared a comprehensive IT specification document, which included in-depth change requests for IT systems and detailed instructions for the automated workflow based on real-time dispatcher (RTD) functionalities. We developed a sophisticated and robust status model to monitor lots and orders and decide on the respective data transfer, assignment, and error handling. A master database and an associated user interface (UI) were devised for human operators. Here, the initial focus was on processing productive lots (i.e., lots that lead to an established and saleable customer product) due to their high overall proportion of quantity, value, and required working time.

After successful programming, testing, and training, we additionally integrated the process of handling development lots in the automated workflow. Development lots influence the LTOM process at IFD as respective orders require different IT systems and usually a dedicated lot requested by production planners. At the end of Phase 1, the initial LTOM process has run through the first round of digital transformation, being successfully automated and rolled out for productive and development lots at IFD and transferred to other fabs in the corporation (e.g., IFAT). The new UI enables employees to view the current overall demand, current orders, and currently available lots. Several buttons are available to manually (re-)start the data transfer of demand and orders and initiate the automatic LTOM process and start date assignment. The workflows are conducted by RTD rules based on predefined criteria and capacity limits, which also include a check of the attributes, material characteristics, and wafer specifics for each lot. Thereby, several IT systems were connected to the UI. A weekly plan for the scheduled lot starts is generated automatically and updated after each execution. Viewing access to the UI is given to all stakeholders, while a role system controls the individual rights to edit and change data. Thus, the broad access to crucial LTOM process components (e.g., the current allocation and lot start plan) facilitates its efficiency, transparency, and connectivity.

B. Phase 2: Optimization

For the second phase, the work packages were integrated into a similar business project running in parallel at IFAT to yield (resource) synergies, reduce efforts, and jointly align and optimize the workflows and IT systems. The IT specification was enhanced by detailed descriptions of additional requirements relevant for Phase 2. Thus, the master database was consolidated within the IT landscape, and the UI became more functional and user-friendly. The implementation of the lot split flag, and additional alerts increased the transparency and flexibility of the LTOM process. Lot split flags ensure the matching of rolling order forecast with split minimization, i.e., the lots of orders forecasted with significant volumes within the next four to eight weeks must not be split into separate units and smaller lots. Thus, slight over-deliveries might occur, which are balanced within the supply chain. We conducted a simulation study to develop approaches for optimal and uniform lot-to-order matching and start date allocation, considering the current product mix, tool equipment, and setup times [11]. The released batches and splits are now evenly distributed. Furthermore, we included multiple constraints to enable real-time processing. The optimized LTOM and start date allocation processes are now displayed in the UI as part of the new “order book”, decreasing onerous e-mail communication and confusing datasheets. Specifically, the development lots’ workflow was enhanced through automated experimental management and an optimized prioritization and shipment process. Lastly, the LTOM procedures and underlying IT architectures were adjusted to be migrated to the 200 mm production line.

III. RESULTS

In this section, we present the results of the project, including potentials for qualitative and quantitative KPIs as well as emerged challenges and how we tackled them.

A. Potentials

We explain the project’s positive results by a variety of meaningful qualitative and quantitative KPIs. In our study, qualitative performance improvements (i.e., hardly measurable in terms of tangible numbers) relate to an increased degree of process standardization, robustness, and digitalization, as well as enhanced employee satisfaction. During the project, several local (i.e., IFD internal) and global (i.e., IFD and IFAT) IT systems and workflows were standardized, consolidated, and enhanced, including the alignment of productive and development lot procedures. For the LTOM process, IFD and IFAT now use a uniform and extensive master database and respective UI that transparently displays the current allocation and scheduling plan. The data transfer improved from a fixed weekly key date to a continuous and nearly instant transmission. Thereby, the developed status model for lots and orders enables appropriate tracking as well as targeted selection and allocation. Both the automated and optimized LTOM process and the start date allocation follow clear, rule-based instructions and allow for a parameterization and weighting of various criteria. Therefore, employee-related process habits were standardized, and errors arising from tedious processing diminished. Although the assignment is done by RTD rules automatically, manual interventions and changes are possible at any time, triggering a new RTD iteration and, thus, ensuring process flexibility and effective monitoring by human operators.

Robustness and predictability of the LTOM process further increased due to the implementation of the lot split flag as an essential control parameter and the uniform and even distribution of lots over the day and week. We digitalized the LTOM process by removing different, organically developed data sources (e.g., outdated data sheets and self-developed IT tools) and diminishing multiple feedback loops based on mail and telephone communication between the involved departments. The automatic assignment of available lots to suitable orders and the wafer start planning were considered the most significant improvements. Furthermore, we could substantially decrease or even eliminate manual efforts for data collection, entry, and maintenance. Thus, the interviewed staff concurred with increased work satisfaction due to the shift from mundane and operational activities to more creative and valuable tasks. The employee acceptance of the newly implemented UI is equally high and further facilitated by profound training. Currently, we are developing an approach to quantify the increased degree of process digitalization within respective KPIs.

Quantitative performance enhancements were realized through improved allocation accuracy, uniform lot start and split distribution, setup-optimized lot starts, increased average lot size, and working time savings. The allocation accuracy measures the degree of over or under-delivery of orders, with a tolerance for accurate allocation of plus/minus one wafer. As a result of the project, the allocation accuracy increased by more than 30 percent, while the standard
deviation has been reduced by 75 percent compared to the state before the project (see Fig. 1). This improvement could be realized due to the transformation of expert knowledge into precise RTD rules, i.e., the automation and standardization of the former manual and error-prone allocation procedure. Besides, the data landscape is now more consistent, displaying the fulfillment of current orders in real-time and providing instant feedback on split aborts. Thus, an increased allocation accuracy resulted in lower excess production and lower inventory levels, while the delivery reliability remained stable. It is important to note that the applied allocation accuracy is related to dies to warehouse (DTW) and dies to orders (DTO) as applied in [2], [4], and [6]. DTO represents the share of dies successfully assigned to customer orders, while DTW constitutes dies that remain in the warehouse. The results are promising and on the same level or even outperforming the findings from previous literature. For example, in [4], a DTW improvement of 23.5% was achieved in experimental settings.

The distribution of lot starts and daily unzips in particular is now relatively uniform, while the respective standard deviation was almost halved (see Fig. 2). Daily unzips describe the number of technical wafer extractions from carriers per day. Fig. 2 illustrates that before the project, the distribution of daily unzips fluctuated more since unzips were scheduled on specific days due to high technical and administrative efforts. Besides, the average lot size has been smaller, which correlated with a higher probability of unzips for lots with less or equal twelve wafers. Thus, the figure also indicates the freed-up machine capacities due to the automatic and smoother unzip distribution.

The fixed weekly date as the determinant for data transfer and distribution start of lots has been eliminated, resulting in this day being entirely usable for lot starts. The lot sectioning now runs more evenly due to the rolling and automated LTOM process and start date distribution. The median of started lots per day has improved by 56 percent, whereas the standard deviation could be reduced by 25 percent. Focusing on the lot distribution, we observed a higher median of lots per hour and a reduced standard deviation by 49 percent. Instead of three usual peaks per day (2 am, 12 am, 6 pm), the distribution is now smoother. This fast and uniform release also reduces cycle time due to increased tool utilization, OTD, and order quantity compliance. At the first processing work center after the die bank, the coefficient of variation of arrival times of incoming lots (CoV_in), as a performance indicator to measure the standard deviation against the mean of the distribution, was reduced by 34 percent (see Fig. 3). Thus, the uptime manufacturing utilization and moves (i.e., completed operations at the work center) enhanced substantially during the project term.

Furthermore, the lot split flag implementation led to an increase in the average lot size from 13 to 17 wafers per lot. Consequently, IFD benefits from headcount and manual effort savings in the defect density inspection as fewer wafers require testing due to the increased lot size. For LC staff, being at the heart of the project, manual efforts decreased by about 80 percent, facilitating a release of 20 percent of weekly working time that could be applied for more valuable tasks. The resulting overall working time savings (including all affected departments of IFD and IFAT) are calculated at around 500 workdays per year.

B. Challenges and applied best practices

Although the project yielded multiple benefits, several complications occurred during the term. The emerged challenges, applied measures, and derived lessons learned are summarized in Tab. I and detailed in the following section.
The first challenge relates to **project organization and management**. At the beginning of the second phase, a somewhat similar project at IFAT came up with related contents and work packages, which would have resulted in cannibalization effects regarding resources and priorities. Therefore, both projects were integrated under the responsibility of a joint project manager to benefit from synergies, double work elimination, and mutual optimization of workflows and IT systems. Consequently, we had to adapt the organizational structure as more stakeholders and managers were involved. Moreover, crucial milestones were negatively affected by short-term changes in priorities and available resources in favor of other essential projects. Thus, we had to dynamically adjust the work packages’ scope, deadlines, and goals to the actual resource availability. Besides, early and vigorous requests for critical resources, such as RTD programmers and employees in charge of realizing change requests for IT systems, minimized the likelihood of further project delays and ensured steady progress. After successfully adapting the project’s organizational structure, we received the necessary management support, and requests for resources were substantially facilitated and accelerated. However, IFD will refrain from a purely static project management approach for future projects but foster agile methods, such as Design Thinking, Kanban, and Time Boxing. The hybrid project management approach combines a determined action framework and organizational structure with agile and iterative (IT) product development. Thus, it allows for enhanced visibility, transparency, and coordination of projects within the organization’s different sites. Furthermore, we recognized that the two project phases were too imprecise and limited flexibility. Therefore, similar initiatives should be divided into clearly distinguished and detailed phases, e.g. (1) pre-study, (2) enabling, (3) automation, and (4) optimization.

The next challenge belongs to **common process understanding and harmonization**. Since the target solution developed for IFD was meant to be transferred to IFAT, multiple stakeholders from both sites had to be involved from the very beginning of the project. That included the consideration and alignment of as many stakeholder requirements as possible. Initially, the LTOM processes of IFD and IFAT showed substantial differences concerning procedures, regulations, and underlying IT systems. Moreover, each stakeholder focused on its own (local) issues and set its requirements accordingly, mostly neglecting the global impact. Thus, we first had to create a common understanding of the upstream and downstream processes and the potential impact of automation. That was facilitated by process modeling and workflow visualization. We intended to develop a global solution, i.e. an aligned and standardized LTOM workflow with benefits for all stakeholders, using Design Thinking. Although we established various technical jour fixes, the information exchange and progress making was too slow. Therefore, the agile methods Kanban and Time Boxing were applied, assigning specific work packages and tasks with fixed deadlines to each stakeholder. Furthermore, we organized several full- and multi-day workshops at IFD as well as mutual site visits to understand how processes work at different fabs. Consequently, some initial requirements were changing, necessitating continuous updates and consistency checks of the developed IT specification. This iterative procedure was closely aligned with the IT departments of both sites, which are in charge of the technical implementation and RTD programming.

The vital consideration of as many stakeholder requirements as possible resulted in another challenge since the IT and process complexity level increased with each modification and additional request, impeding the alignment
of workflows and systems. We underestimated the interdependence and integration of the various IT systems, although we developed a detailed IT specification document and a robust status model for lots and orders beforehand. IT tools providing input for but not specifically relevant to the LTOM process were still indirectly affected by the change requests as they also required adjustment and certain new functionalities. Thus, we recommend a comprehensive, profound, and forward-looking assessment of the potential IT complexity as early as possible for future projects, involving IT and programming experts as well as process owners and specialists. The estimation should match short-term and long-term goals with respective adjustments of tools and workflows to develop a robust concept with limited autonomy. However, the draft should also provide certain flexibility to react to unforeseeable (external) effects, such as changing resources and priorities.

Finally, the decision on the technical automation and optimization approach of the LTOM process was challenging. We opted for the deterministic form with predefined algorithms and rules for the RTD. However, each adjustment or add-on results in increasing complexity for programming and maintenance. Therefore, we tested a more dynamic, mathematical approach and conducted a discrete event simulation study that showed promising results [11]. Although the current LTOM process is stable and highly automated, IFD seeks to replace the RTD rules with a mathematical solver if the complexity increases.

IV. CONCLUSION AND OUTLOOK

In this paper, we present the approach of an automation and optimization project for the LTOM process of 300 mm production lines at IFD and IFAT. The former manual process was analyzed and standardized to enable it for automation. Next, we focused on further optimization of the process and the affected IT systems and artifacts. This article includes the applied measures to several emerged challenges related to project management, the LTOM process, and technical issues. However, due to the pleasing results and considerable positive effects on essential qualitative and quantitative KPIs, such as delivery reliability, throughput, customer satisfaction, and workload reduction, the project is judged successful by all stakeholders. It contributes positively to the organization’s competitiveness and level of digital transformation.

Future work will comprise the further optimization of the start date scheduling, including the display of the current tool setup, daily and automated capacity checks of manufacturing tools for productive and development lots, and a compound order start. Therefore, the organization integrates a new ERP system and intends to develop a more precise solution based on a mathematical solver. Furthermore, we aim to improve the error handling and monitoring of lot splits and enhance the IT tools and UIs towards an even higher flexibility, user-friendliness, and performance. Thereby, the final transfer of the LTOM process and IT systems to the 200 mm lines of both sites will be facilitated.

Our study comes with certain limitations. Although we conducted a longitudinal in-depth case study considering two fabs and multiple sources of evidence [9] to address the lack of empirical research for the 300 mm LTOM process, there are limits to the generalizability of the results. Indeed, specific workflows and IT systems are unique for IFD and IFAT. Besides, both sites follow the More-than-Moore strategy aiming for broad diversification through high product variety. This approach implies different objectives and prerequisites than for companies pursuing the More-Moore strategy [1]. Therefore, we call for further in-depth or cross-case studies considering both doctrines to confirm, complement, or disprove our findings. Moreover, a comparison of approaches for 200 and 300 mm lines is expedient.

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