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AN AGENT-BASED SIMULATION MODEL WITH HUMAN RESOURCE INTEGRATION FOR SEMICONDUCTOR MANUFACTURING FACILITY

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ABSTRACT

This paper presents an agent-based simulation modeling of a real workshop of a semiconductor factory. One of the main characteristics of the factory is the strong involvement of human resources in production operations. The purpose is to build a simulation tool to help decision-makers anticipate production issues. To do so, we defined hypotheses and built a model integrating operator characteristics. The simulation results are based on real industrial data from the company. We foresee how the evolution of the production is difficult to handle. Due to the complexity of the outputs, we introduce a new metric and used it to analyze the results. Finally, we release a conclusion and perspectives in which we give our opinion on the building and use of such a complex model in an industrial environment.

1 INTRODUCTION

Semiconductor manufacturing process begins with raw wafers which are thin disks of silicon or gallium arsenide. Typical insert diameters are 150, 200 and 300 millimeters. Several thousand identical chips can be produced on a single wafer. The processes are done layer by layer on the wafer. Wafer fabrication plant is called a fab. We can have up to 40 layers depending on the complexity of the device being produced (Mönch et al. 2013). A fab is made up of different work areas (or workshops). They include oxidation, photolithography, chemical mechanical polishing, diffusion, film deposition, implant (doping), and etching. A workshop contains different workstations (Hutcheson 2000). Workstations are closely linked logically or with their location. A workstation is a collection of machines that offer similar processing capabilities. The wafers are collected in an entity called a lot. A lot contains a maximum of 25 wafers (sometimes 50 wafers depending on the diameter). Some machines can only process one wafer at a time, while other types of machines can process multiple lots together. Batch and cluster tools are typical for the semiconductor manufacturing process. A batch is a set of lots that are processed at the same time on a single tool. A cluster tool can process different wafers simultaneously with different process steps (Lee 2008). To move

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from one workshop to another, a lot can wait inside a stocker until a machine is available. Stockers serve as an interface between workshops. A stocker is a rack storage area where lots can be stored before and after processing. Operators are human resources who help to transport lots between different workshops, load and unload machines, etc. All these processes and the number of machines, workshop operations (parallel scheduling, batch scheduling, etc.) make the semiconductor manufacturing process one of the most complexes that exist, as described by Gupta et al. (2006) and Uzsoy et al. (1994).

Figure 1 gives an overview of the production flow system. It describes how a wafer can enter the workshops several times before the end of production. Figure 1 does not fully display the entire fab layout as there are more workshops in the real system. The final product is a printed chips wafer. It ended the production part called front-end manufacturing to reach another step to be prepared and tested before delivery. This next step is called back-end manufacturing and is not part of this study.

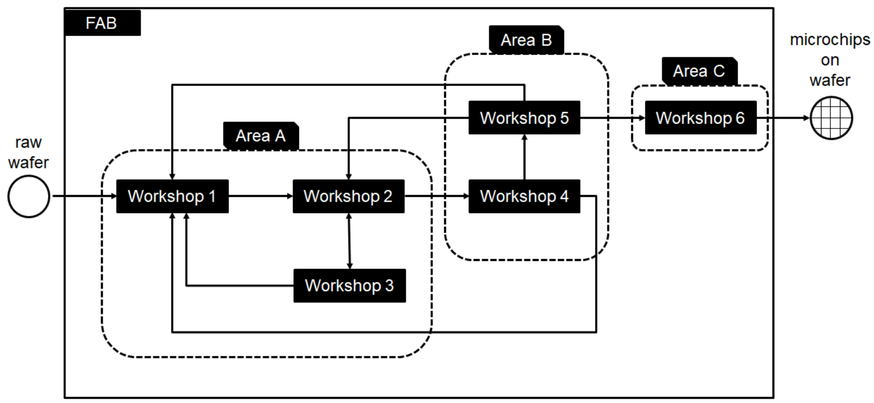

Figure 1: Example of the production system layout.

As already written, most of the problems encountered in semiconductor manufacturing are complex. There are different approaches to solve these complex problems. Mathematical approaches are one of them and allow to get certain success results (Mönch et al. 2013). But usually, these approaches are difficult to use due amongst others to non-linearity (Lu and Yuan 2007). Currently, agent-based simulation approach seems to be more appropriate for these complex problems, see for example Jin et al. (2008), Chong et al. (2006) and Ben-Salem et al. (2017). This type of simulation has the particularity to describe with more details the complexity of the interactions occurring within the production system.

Simulation (discrete-event (DE), System dynamic (SD) and agent-based (AB) (Borshchev 2013)) are the main simulation techniques used to address problems in manufacturing system design and operations (Negahban and Smith 2014). Specifically, they have been applied for various applications in semiconductor manufacturing. Articles of Low et al. (2006) and Lin et al. (2015) describe simulation systems for semiconductor assembly and test operations. The authors as Lin et al. (2014) propose a simulation-based optimization approach for an automated material handling system in the photolithography area. Simulation is extensively applied in scheduling and optimization problems for semiconductor manufacturing, as demonstrated by Gupta et al. (2006), Siegfried (2014) and Zhang et al. (2009). However, few articles are dealing with the simulation of semiconductor manufacturing processes including human resources as the operators. As an example, Crist and Uzsoy (2006) address the importance of technical support staff in wafer factories using simulation. Spier and Kempf (1995) presented a similar approach, using generated data, their simulation is used to find the best organizational behavior the operators should adopt to maximize the factory performance. The main reason there are few articles including human resources in their studies is that the equipment is so expensive that most of the papers focus on them. In addition, factories are becoming more and more automated, and modern factories have a higher level of automation which requires more expensive machines and fewer operators. This situation leads to optimize the operation of the machines rather than the operator operations. However, many existing factories strive to improve their manufacturing processes by working on operator management.

The purpose of the article is to create a simulation tool to help managers anticipate production issues. It integrates specifically the involvement of human resources in the production system and the main existing interactions between the operators and the production system. The ability of the simulation to match the reality is also measured through indicators.

The rest of the paper is organized as follows. Section 2 describes the main parts of the model. The idea is to give readers enough information to understand how it works. Section 3 contains the results of the study carried out on real data from STMicroelectronics. We also highlight how the performance metric is constructed and discuss its strength, shortcomings and its originality. Finally, we conclude and give some perspectives in Section 4.

2 WORKSHOP MODELLING

This section describes the main components used in agent-based modeling. These are the Entry and Exit of a workshop, the Stocker, the Production Interface, the Machine and the Operator.

Before describing the model, let us summarize the definition of agent-based (AB) simulation modelling. AB models the system as a population of individual objects (agents or active entities) that communicate with each other and follow a series of rules to achieve their specific objectives. Communication is provided by a set of messages which includes the agent send a message, the agent receives the message and the content of the message. AB is suitable for modeling complex systems (Siegfried 2014).

A workshop is part of the fab. It contains a collection of machines that offer similar capabilities. The workshops remain connected through the different lot flows. We start by building a generic model able to reproduce the functional behaviour of a workshop. We apply it to a pilot workshop and, depending on the results, we will generalize it to other workshops. To describe the operation of a workshop, we follow the progress of the lot within the workshop.

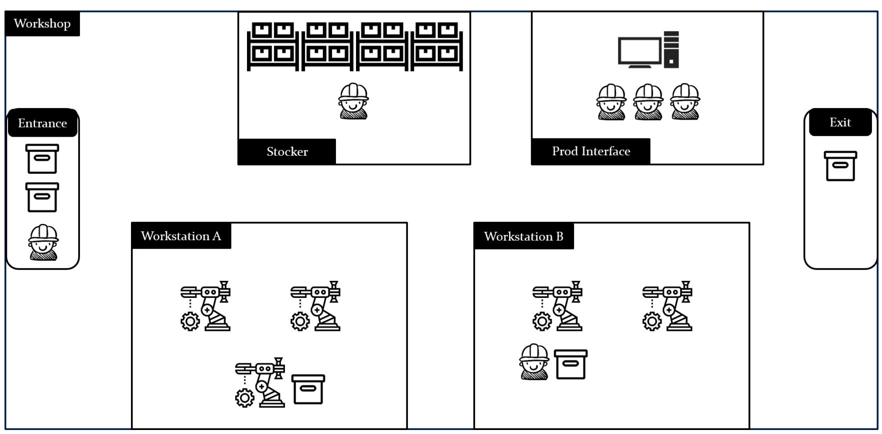

Figure 2: A representation of the workshop modelling.

The generic model that we built is illustrated in Figure 2. A lot enters at any time and is delivered by an operator from the previous workshop. The entry of the lot is also defined as an operation. An operation is a succession of processes that the lot performs before leaving the workshop for the next. To become the final product, the lot follows a route (specific to the type of product) which is a succession of operations. Once the lot has entered the workshop, an operator leaves it at the entrance. It is an agent modeling the rack assigned to the arrival of the lots. The lot waits there until an operator from this particular workshop brings it to the stocker. This action models the lot recording by the operator. And, from now on, it is included in the workstation's WIP (Work In Progress). This implies that the lot can be scheduled on the machines. The stocker is an agent that manages the scheduling of lots according to the next process to be carried out. The availability of qualified machines (capable to process) and the relative priority of this lot compared to the priorities of the other lots. Priority is a numeric value representing the speed at which the lot must complete the operation in progress. Once a capable machine is found, the lot is the next to be considered according to the priority. The stocker informs the production interface that there is a lot to deal with. The production interface is the agent modeling fab's computer system. It can be a computer or a simple screen where information is displayed for operators. From there, operators retrieve the states of the machines and lots waiting for processing to assess the situation, then decide which lot executes next. The operator, after choosing the action, retrieves the lot from the stocker and brings it to the machine. The operator loads the lot onto the machine and the process starts. Depending on the type of treatment, the operator leaves the machine to find another lot to perform or stays until the end of the process. In the latter case, the operator brings the lot back to the stocker if another process is planned or, delivers it to the exit. If the process is automatic, the machine sends a signal to the production interface to indicate the need for an unloading action. The exit is an agent modeling the fact that the operator prefers to deliver lots by a group rather than delivering them one by one. This agent has no other objective than to force the lots to wait before going to the next workshop on their production route.

2.1 Entrance and Exit

As already described, the entrance and exit are both agents modeling waiting areas for lots. The entrance receives lots by operators from other workshops. Many can enter at any time but are not always considered immediately. It is only a buffer zone. The entrance has a parameter called capacity, representing the storage limit in the number of lots. The limit is checked promptly and if the number of lots exceeds it, the entrance sends a message to the production interface asking it to retrieve the lots currently stored. Another mechanism is included to avoid issues. If the workshop starts to be empty and there are not enough lots in the entrance, the lots will wait a long time while they could be processed on the machines currently available. This is why security has been added. The production interface can ask an operator to retrieve lots at the entrance, if there are not enough lots in front of the machines. Even if the capacity is not reached. The Exit works in the same way, except there is no need for such security. The only difference is that it manages two different capacity parameters: the minimum and maximum capacities. The entrance is always listened to by operators and is considered a top priority as it provides the workload. The operators are more determined to receive lots than to deliver them. This behavior is inherited from the specific way the company evaluates the performance of operators. The way the performance indicator is calculated implies that the delivery of a lot to the next workshop is not considered in the evaluation. Operators, therefore, prefer to see the number of waiting lots increase until the delivery is worth. This is why this agent contains two capacity levels. When the minimum capacity is reached, the operator will only start a delivery if there is nothing else to do. When the maximum capacity is reached, the operator addresses it immediately because there is a risk of emptying in the next workshop.

2.2 Stocker

The stocker is an agent used to store the lot currently in the WIP. When an operator brings a lot to the stocker, it dispatches the lot on all the compatible stocker-machines (a subdivision of the stocker proper to a specific machine). It is considered compatible if the corresponding machine can perform the next process in the lot route. This way, a stocker-machine contains a list of every lot waiting to be treated. Once a stocker-machine has scheduled the lot like the next one, the other references are suppressed in all the concurrent stocker-machines. Whenever a tool is available for loading, it sends a message to the corresponding stocker-machine which schedule the next lot. In the real world production system, the operator decides what is the next task to perform but here, to synchronize operator actions, it was easier to centralize this scheduling process. However, we implemented a realistic and deterministic scheduling policy based on our field observations and the consigns given to the operators. The scheduling is based on campaign scheduling. A campaign contains several lots that have to be treated consecutively because of the machine set-up times. Longer is the set-up time, larger is the campaign size. The lots are batched based on the highest priorities found (highest priority, with the second one, ...). And the campaign is created around the highest batch priority. The only exception to this rule is caused by time lag constraints. After a process, a lot can be forced to wait a specific amount of time before its next step. On the contrary, some processes require them to perform the next step before the end of a time constraint. Whenever a time lag constraints could be violated, the scheduling advantages its respect over the priority policy. Once the stocker-machine has decided what is the next lot to load on the machine, it sends a message to the production interface to demand the creation of a task. When an operator is available to perform it, the lots contained in the campaign are retrieved and brought to the machine starting with the first lot.

2.3 Production Interface

The production interface is an agent modeling the computer system. In the real world system, operators can retrieve the data about the lots in WIP and the states of the machines from it. Based on the data, the operators decide what is the next task to perform in the workshop. The first purpose of the production interface is to gather these pieces of information and create appropriate operational tasks. This interface must interact with all the agents to display useful pieces of information. The machines communicate their states when they need to be loaded or unloaded. The entrance and exit send a signal when their capacities are reached. The operators inform it when an action is realized too. The tasks are stored in a list, waiting to be performed. The second purpose of this agent is to assign tasks to the operator. The operator receives a list of compatible tasks and decides what is the one to perform in priority. The compatibility of a task with an operator is due to two factors. The first one is the workstation where the operator is assigned. A workstation is a group of machines and, at the beginning of every shift, the operators are assigned to a specific workstation. The production interface will not propose a task that is outside the operator's workstation range. The second factor is the abilities of the operator. To perform a task, the operator must be trained to perform it, otherwise, the production interface will not propose it. The task has a type but also contains a list of actions to perform. For example, to realize loading, the task includes all the needed actions like the movements to do, the lots to retrieve or drop, and the machine to load or unload. Doing so, the task already embeds all the context of execution based on the current situation of the workshop.

2.4 Operator

Figure 3 displays the statechart regulating the operator's behaviour. In the simulation, the operator starts while waiting for the production interface to propose compatible tasks to perform. When the task list is received, the most urgent is selected. The operator decides, using a diagram, the relative priority order of these tasks. The decision made is mainly based on the types of tasks. For example, emptying the entry is often considered a priority before emptying the exit agent (operator modeling will favor actions that increase their performance metrics). Of course, for the same task type, like a loading type, this is the priority of the batch which will matter. An operator can store a given number of tasks in memory. Generally, the operator does not check the system each time a task is performed but prepares actions in advance. The first task to be performed is selected according to its relative priority and the operator begins by re-factoring it. When an operator has several lots to retrieve, the number of "movement actions" may differ if a trolley is available. This is the purpose of this re-factorization step: adapting the execution of the task according to the context. Then, the action is executed and the operator processes the next action until there are none left. When the current task is finished, either the operator executes the next one he has in memory, either he returns to the production interface to obtain new tasks.

One of the main challenges encountered during the simulation model development is the agent synchronization. It is always necessary to secure the interactions to avoid that several operators work on the

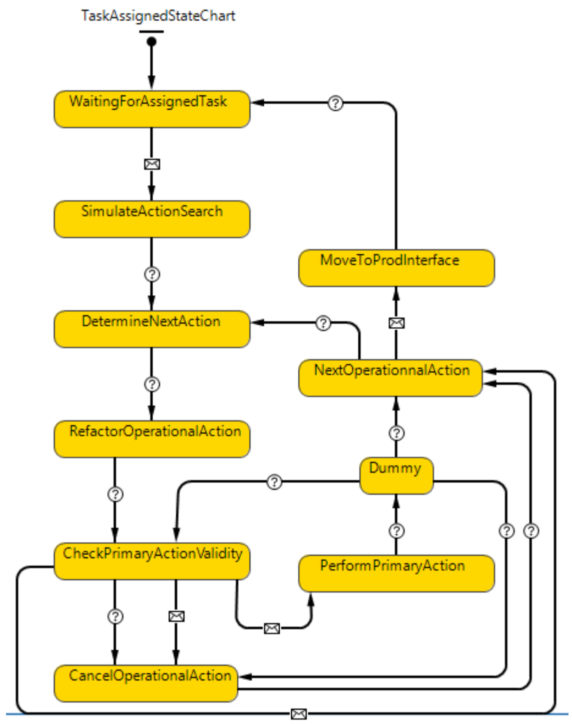

Figure 3: The state chart of a generic operator.

same machine, search for the same lot, or accept the same task. If the operator tries to retrieve a lot from the stocker and, if the lot is not currently inside, the stocker rejects the task, and the operator must drop it. An error message is written in the logs to warn the user, as it is not an expected behaviour.

2.5 Machine

The machine is a generic agent designed to model all types of machines existing in the factory. Figure 4 shows the state diagram of the machine agent. The model itself does not reproduce the process to be performed at the wafer level but, computes the processing time differently depending on the scenario. The machine behavior changes according to its parameter values defined during the initialization and the input data of the simulation. One side of the statechart is used to perform a loading action, while the other side is dedicated to the unloading action. At the beginning of the simulation, the machine starts empty in a waiting state and sends a signal to the stocker. When the operator comes to load a lot, the machine checks whether the lot corresponds to its specification then accepts or not to be loaded. If the loading action is accepted, the machine will consider the operator as a resource and manage the computing time of the loading itself. If the process is automatic, the operator is immediately released after the loading and can perform other tasks elsewhere. If the process is semi-automatic, the operator is released after a certain time according to the process specifications. When the process is manual, the operator cannot leave until the process is completed and will automatically perform the unloading action. In the case of automatic and semi-automatic processes, since the operator left before the end of the process, the machine warns the production interface that an unloading action is required. When an operator unloads, the machine behaves similarly. The only difference is that the machine allows the operator to restart a new process if there were already enough wafers waiting on the machine. Some machines cannot work on an entire lot at a time, and the process must be restarted several times to process a single lot. Once the unloading is complete, the operator is released and the machine alerts the stocker that it is available before returning to standby.

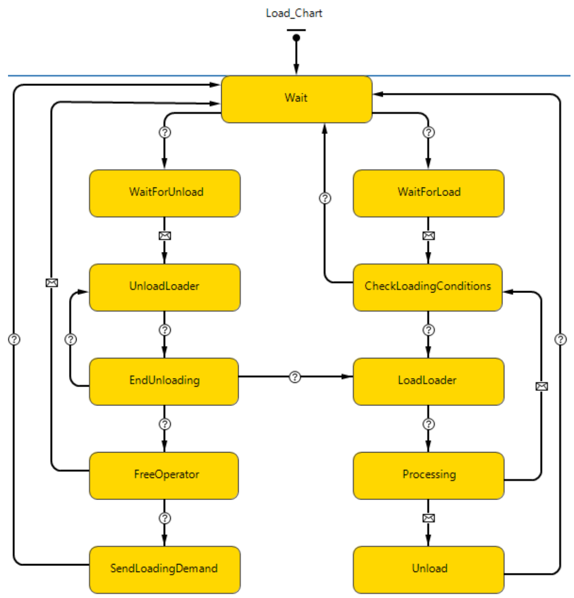

Figure 4: The state chart of a generic machine.

3 RESULTS

In this section, we start by defining the indicators used for analysis then we describe the results obtained on real instances of the fab.

3.1 Performance and Metric

To validate a simulation, it is important to refer to the real system and the way one assesses the situation. In our case, there are three important indicators used to describe what happens inside a workshop. The first one is called MOVES. For example, a lot containing 50 wafers generates 50 moves after going through all of the operation processes (a single operation per visit to the workshop). The second indicator is named OUTS (for outputs). It has the same structure except that an OUT is generated each time a wafer has completed a process on a tool. These indicators, OUTS and MOVES, describe the amount of work that has been completed during a period. The third indicator is WIP. The WIP is a measure that assesses the number of wafers waiting for treatment or being processed inside the workshop. WIP allows management to measure the remaining workload and how it is partitioned. WIP is an instantaneous indicator because it evaluates a value at a specific moment. The main complexity of the analysis is due to many different operations and products involved in the production. Indeed, for the same amount of wafers in WIP, the situation can be radically different depending on the product mix. The same logic can be applied to MOVES and OUTS. If the analysis is solely based on the number of wafers, it will not fully describe the situation and will also create a bias in the interpretation. For instance, the simulation may find the correct amount of wafers while describing a very different situation considering the product mix, implying a different way to manage production. Indeed, it is also essential to measure the divergence in the mix because the number of steps and their duration can vary considerably from one product to another. Also, managers will not be able to correctly evaluate the situation despite a possible good performance of the simulation. Our analysis uses three types of precision levels: the workshop, the products and the products at operation. The products contain more than 20 possible categories meanwhile products at operation contain more than a hundred of them.

3.2 Experimental Tests and Results

The model is developed with AnyLogic version 8.4. We have conducted the experimental tests on industrial data extracted from databases. The period lasts 4 days and the situation is assessed every half a shift (4-hour period). To measure both the difference in mix and quantity, we have chosen to use the Euclidean distance between reality and simulation. The points are placed in an n-dimensional space (here n is the number of categories within the level of precision studied). This means that the observed indicator can be described as a position in n-dimensional space. The Euclidean distance is measured between the reality and simulation points. The distance itself is difficult to grasp. Thus, the ratio between the distance reality-simulation and origin-simulation (the origin is the point containing 0 for each coordinate) is expressed. The lower the percentage, the better the performance. The main advantage of this approach is its simplicity. The drawback is the loss of information. It is impossible to determine whether the divergence is due to a difference in quantity, mix or both. Therefore, the measure of the difference in the number of wafers is also given in the results. Figures 5, 6 and 7 respectively display the results for MOVES, OUTS and WIP indicators.

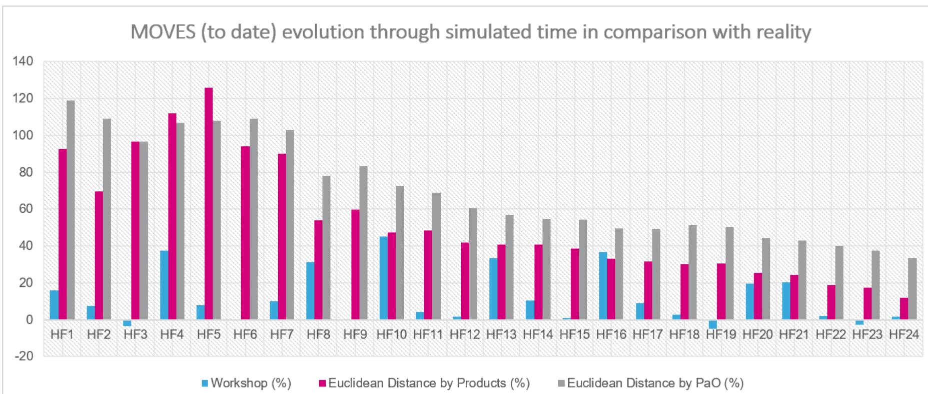

Figure 5: Evolution of MOVES-to-date divergence through time.

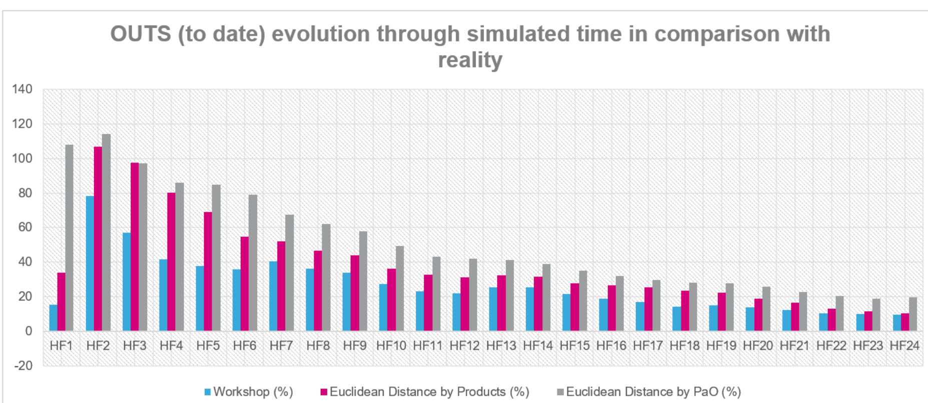

Figure 6: Evolution of OUTS-to-date divergence through time.

The results were tricky to analyze due to the high number of steps and products involved. The main source of discrepancy is certainly due to the differences in lot schedules. Indeed, the production system is controlled by operators, each managing their workstation according to the instructions given by the production management and the state of the tools. In the same situation, two different operators must not react in the same way. This is why trying to reproduce the same scheduling policy is very tricky considering.

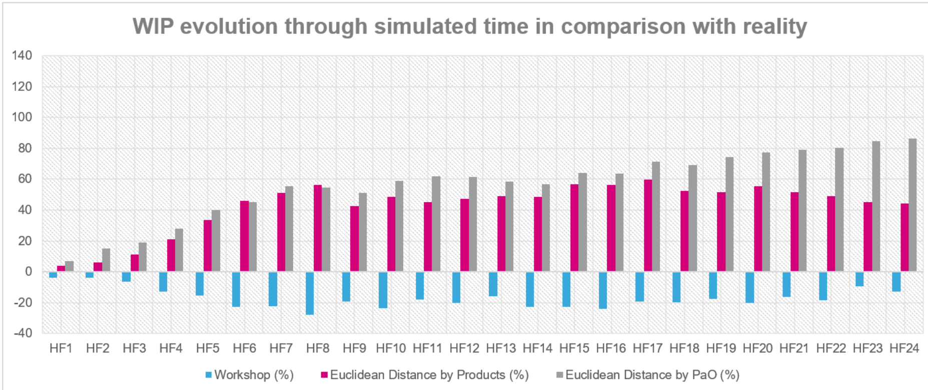

Figure 7: Evolution of WIP divergence through time.

Also, it is the operator who decides on the task order. This state of affairs leads to the impossibility of predicting an exact situation at a given time. We were also unable to reproduce exactly the initial positioning of the lots in front of the machines. This fact is a cause of divergence too, but weaker than scheduling. We believe it is possible to reduce this divergence by integrating new functionalities (reproduction of machine unavailability, starting lot processing directly in the machine, etc.). But the gain will probably be limited taking into account the sum of the efforts to deploy to do this.

The evolution of the divergence is interesting to note. A specific pattern appears, very different at the start, then the result of the simulation slowly approaches reality until the end of the period. At the end, the divergence is small. Based on our experience, we expect the simulation to deviate slowly over the next simulated days before the divergence increases rapidly again. This is true for MOVES and OUTS because we have expressed them as cumulative values. However, this interval should be discussed giving the final objective of the simulation and after testing different data sets. We first evaluated the behavior of the simulation with reality and examined the performance indicators to determine what is possible. We mention that the performance indicators are new and may not be the best of the various possibilities available. However, the problem posed by the scheduling is clearly expressed by the WIP. This indicator tends to show that it will be extremely (or even impossible with this model) to obtain a simulated situation close to reality. An interesting thing to note is the apparent stability of the WIP divergence from the 8th half shift.

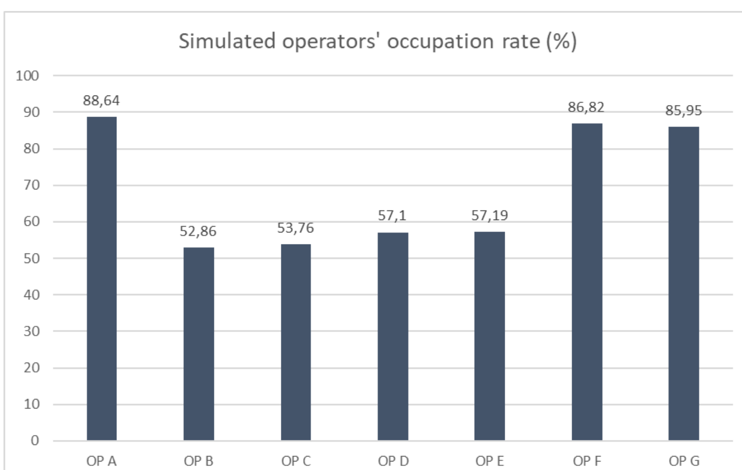

Figure 8: Simulated occupation rate of operators.

Figure 8 shows the occupation rate of operators during the simulated period. Occupation is defined as the set of all the tasks that operators perform to run the production system. This includes break times, meetings, and normal production activity, including lot processing. The model excludes other operator roles that are not productive. The difficulty here is that we cannot compare these results to what is happening in reality. The real indicators following the operators throughout the shift do not exist. And, more generally, everything that does not relate to direct production is not recorded or accessible to us. However, based on the feedback from employees (operators, engineers, and managers), the results on the operator occupancy rate are consistent with reality, given the specificity of the period. Some operators may be more or less productive depending on the current workload available. While others prefer to give extra time to other tasks outside the scope of production, but useful in other ways. An example of non-productive tasks is the analysis of lots requiring a rework. At a given point in its route, the lot is checked to ensure that it meets quality standards. If not, the operator job is to determine the cause and how to fix it. In case of doubt, the operator's responsibility is to inform the right person. This indicator helps to check if the operators behave correctly and it seems it is. However, due to the lack of data, we are unable to prove it.

4 CONCLUSION AND PERSPECTIVES

The paper presents a simulation model to help semiconductor manufacturing company having a better understanding of the production flows. An agent-based simulation has been built with an emphasis on operator management. Also, the main components of the model have described their behavior.

As the simulation is surprisingly precise in the medium term for the cumulative indicators, it could be relevant to use it to measure the evolution of the workload and determine the production targets accordingly. For this use, the simulation measures the ability of operators to carry out production and gives the manager an overview of what could be done within a certain time. However, predicting the evolution of flows and risky situations seems difficult to do. The order of execution of the tasks being different, the WIP will always evolve differently from predicted. We might be able to foresee the biggest problems, but they will occur at a different time from the one predicted by the simulation. This approach could be valid if production is carried out by a known scheduling policy reproducible by simulation. In this case, it could be very profitable to use the model for this purpose. In the same way, instead of making predictions, the simulation could be used to determine the scheduling policy to adopt, considering the current situation of the workshop. In this case, the simulation is coupled with an optimization tool. There are also other possibilities such as using simulation to determine the best workstation assignment for workers or what skill sets need to run the workshop in the best possible conditions. There are numerous options, but we recommend limiting the simulation to a specific use to avoid creating a chimera that is impossible to maintain.

This type of model is complex to develop. It took time to get the right data and validate the model. Also, the model and data should be updated regularly. An expert capable of applying the required modifications can measure the divergence. Therefore, the use of this tool requires dedicated people. Their profiles must be IT-oriented and contain an engineer, a developer, and a production system expert. Considering the divergence issues, the company was surprised by the quality of the results, which is a good indicator of the difficulty in obtaining relevant forecasts in the manufacturing of semiconductors, especially at a low level of automation.

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