A Simulation Model Supporting the Production Optimization for High-Precision Machines Assembly

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Abstract. Simulation has a pivotal role in the Industry 4.0 revolution as a tool to support the decision-making process in the production system. In this paper the model developed for an assembly line of EDM machines is presented and its use to improve the production management approach is described. In particular, simulation has been used to identify a better approach for the dispatching of new job to the line, to optimize the scheduling plan and to develop a training plan for the operators. Obtained results are promising and a further development of the model is foreseen.

Keywords: Modeling and simulation, Planning and control approaches, smart industry

1 Introduction

In the current competitive scenario, companies producing high-precision machines are facing several challenges such as the high level of customization leading to the need of producing several models and variants or the need to maintain an adequate level of work force occupation and resources saturation in spite of a high demand variability. The exploitation of the advanced technologies brought by the Industry 4.0 provides an enormous support to cope with these multiple requests and to improve the production system performance. Among them, simulation tools are considered a possible decision support system. Aim of this paper is to present the simulation model developed with Arena of an assembly production line of EDM machines of a Swiss company leader in the production of high-precision machines. A recent increase in the number of delays occurred in this line along with the difficulties in efficiently managing the resource allocation led the production manager to believe that a new solution that could take into consideration the evolving dynamics of the relevant parameters is required. Because of the variety of products required by the market, the production mix results to be different month by month. Operators' skills are the key to guarantee high quality standards and the respect of delivery times, yet they feature different individual set of skills. In this context, the use of simulation has been identified as the most promising solution that can provide a complete overview of the system and of the interactions between its elements.

2 Simulation in the Industry 4.0 era

A simulation is an approximate imitation of the operation of a process or system [1]: the model represents the system itself, whereas the simulation represents its operation over time [2]. Simulation has been identified as one of the pillars for the Industry 4.0 and should play a central role in industry for the years to come as an enabler of innovative methodologies to plan and control manufacturing systems [3]. In their literature review, [4] identify the main features of the discrete event simulation (DES) that can contribute to the fulfilment of the industry 4.0 agenda, namely automated data exchange, automatic model generation and visualization. On the other hand, as pointed put by [5], industry 4.0 introduces many new modeling demands for DES technology to be able to assess the impact of advanced features, identify areas of risk before implementation, evaluate the performance of alternatives, predict performance to custom criteria, standardize data, systems, and processes, establish a knowledgebase, and aid communication. The use of DES to improve manufacturing performance is widespread (e.g. [6]; [7]; [8]).

3 The simulation model

DES has been chosen due to its possibility to simulate the dynamics of a production system in such a way variation in manufacturing processes, assembly times, machine set-ups and breakdowns can be taken into consideration. DES is a kind of simulation involving events (arrival, departure, etc.) that occur at discrete points in time. Often, DES involves random processes (typically, some theoretical statistical distribution). Arena, the simulation software used in this project, is a DES and automation software developed by Systems Modeling and acquired by Rockwell Automation in 2000. It uses the SIMAN processor and simulation language, one of the special-purpose simulation languages (among the others GPSS, Simscript and SLAM).

Main production processes taking place in the production department have been mapped with IDEF0 and their functioning has been discussed with the experts so to start from a shared vision of the system. At the same time relevant data have been prepared integrating existing data bases with missing information (for example the type of options mounted on a machine was not recorded systematically) and *ReadWrite* blocks have been used to read input data from files that are externally editable so to make easier the simulation use by non-experts.

3.1 Assumption and programming choices

A set of assumptions on the input data and on the functioning of the system have been introduced to develop and run the model:

- standard values have been used for the process times;
- percentage of non-compliant machines and probabilistic distribution of the associated delays are based on historical data;
- operators' skills have been codified and summarized in a matrix to be used as input file for the Arena environment. The training matrix is binary: each

operator is considered to be able or not to perform a certain task, whilst ability can be different depending on the level of expertise

- for each phase, the first free operator is chosen from those able to perform that specific phase (as reported in the relative training matrix);
- at the end of the different lines in the production system there is a shared buffer with a capacity of 6 machines where machines are temporarily stocked waiting for the final test phase.

These assumptions have been introduced to develop the first version of the simulation model, yet most of them can be relaxed in the following versions.

The simulated assembly lines have been graphically represented so that the animation can be used to promote credibility among stakeholders. Given the high relevance of the operators on the line performance a dashboard has been added to monitor some operator's parameters (see **Fig. 1**).

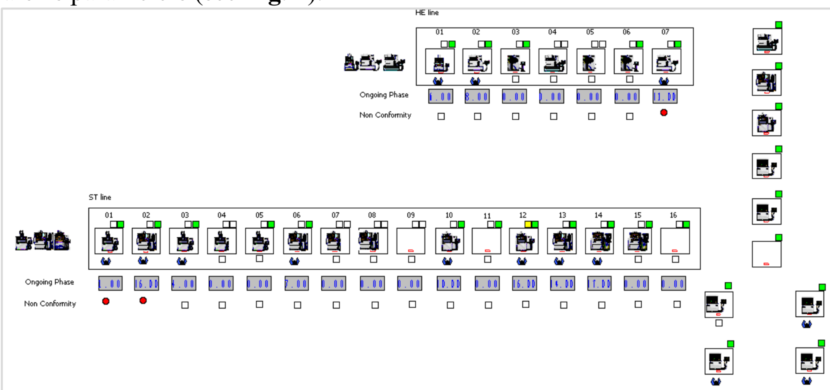

Fig. 1. Simulation model graphics

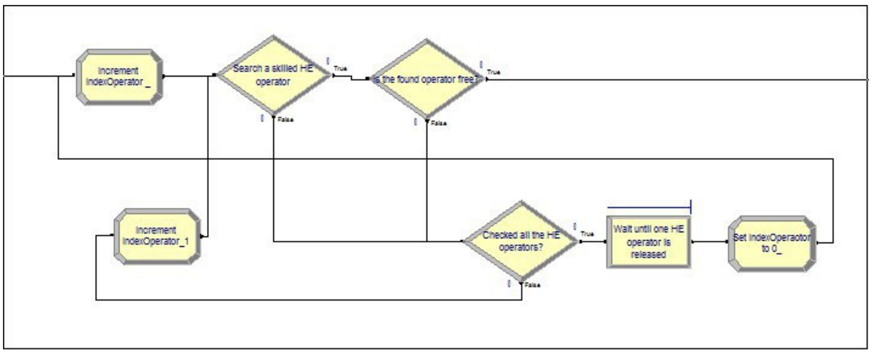

Fig. 2. Operator's search sub-model (Arena code)

The above-mentioned logics of the simulated line have been modelled in Arena by developing differ sub models. As an example, in **Fig. 2** the code for the search of and operator able to carry out the considered assembly line is shown. The code crosses data about machine's family and index of the phase to be executed (saved in attributes) with the competence matrix in order to find an operator with the necessary skills. If no adequate operators are the search continues. After having checked all the operators, if nobody is available, the entity stops in a queue waiting a signal informing that an operator has been released and his adequacy is checked.

4 Model verification and validation

The criteria to establish the correct number of replications for the model is defined in terms of the percentage difference between two subsequent results that does not have to exceed 3%. This happened from the 10th replication on: the number of replications has been thus set to 10. This number allows to reduce the impact on the results of the main uncertainties of the model that are the statistical distribution of the non-conformities times and the probability of having a non-compliant machine in each assembly phase.

The verification of the model, needed to ensure that the implemented model follows the logic for which it has been designed and it is free of bugs and errors, has been mainly carried out by systematically verifying each logical block of the model, with the Arena debugger and making sure that the machines in the production plan have been processes by the right resources.

The final validation, carried out to confirm that the developed model is suitable for its intended use, has taken into consideration 4 KPIs chosen with the support of experts, namely monthly productivity, assembly and overall lead times, work in progress and resource utilization rates. These KPIs have been validated running the simulation with historical data (production plans of June and July 2019) and all results have been judged as valid by the experts. During the validation it was decided to add the modelling of the periodic absences in the operators' teams (e.g. holidays, illness, medical examinations) given their relevance for the overall process. Based on managers expertise, it has been quantified as one operator per week.

5 Use of the model to optimize the production management

The developed simulation model allows the company to analyze in a systematic way data coming from the production system taking into account all the sources of variability and, hence, leading to the creation of unprecedented knowledge about the system dynamics. KPIs such as resources utilization rate or average time in queue, that were not measured before, are now made available thanks to the simulation analysis and support the creation of new knowledge for a more informed decision-making process. The model has been tested as a decision support system aimed at optimizing the performance of the assembly line in three different ways: (i) by simulating the efficiency of alternative dispatching rules; (ii) by simulating alternative monthly scheduling plans to minimize bottlenecks and delays; (iii) by developing a training plan for the operators that could optimize the line performance.

The three analysis have been carried out on the line called ST, producing 5 family of products with a volume of around 500 machines/year, that in the last months experienced several delays. The line has 16 stations where 18 assembly tasks, taking from

1.5 to 2 hours each, are performed by a team of 11 operators. Each machine can be equipped with up to 5 different options depending on customer's request.

The results are promising and are briefly presented in what follows.

5.1 Comparison of dispatching rules

The simulation model has been used to compare the current logic in place (Logic1) to dispatch a job into the line against an alternative one (Logic 2).

Logic 1: as soon as the first station in the line is free, the next machine in the production plan chosen according the earliest shipment date rule is put in the line. As the machine passes through the different stations, the expected delivery date is update. The actual availability of operators and the type of options to be mounted are not considered, thus a time buffer has always to be included in the time estimation. In case of delays, rescheduling of resources is needed and overtime work is requested.

Logic 2: considering the due date promised to the customer and based on a rough-cut capacity planning analysis, a fixed starting date for each machine is calculated. A new machine enters the line only at the predetermined due date and not when the first station is empty. This logic needs to be supported by the simulation model since it allows to assess more carefully the lead time thanks to the consideration of the different options to be assembled and the different skills of operators. Expected benefits are in terms of better work balancing, reduced WIP and reduced delays.

In order to compare the two logics, a variant of the Arena model for the ST line has been developed and the same production plan of one past month (June 2019) has been used to analyze which of the two performs better. In **Table 1** the performance obtained using the two logics are presented. The improvement brought by the use of Logic 2 are evident. In one year time, the time saved (2.7% is around 1 hour/machine) can be as high as 400-500 hours corresponding to the capacity to produce 10 to 15 additional machines. The reduction of WIP allows to easily manage the work force and the space, whilst avoiding to remove machines form the line before they are complete to meet urgent needs, allows the saving of money and time. The most important benefit is the one related to the saturation of operators: they can be trained in other tasks, can be reassigned to other assembly lines or departments contributing to increase the level of flexibility.

Table 1. Table captions should be placed above the tables.

Indicator	Logic 1	Logic 2	% difference
Average production LT (hours/machine)	42.38	41.23	- 2.71%
WIP (no. of machines)	6.18	5.25	- 15.05%
Machines removed before the end	17.2	16.1	- 6.40%
Level of operators' saturation	56%	44%	- 20.95%

5.2 Comparison of alternative scheduling plans

In the ST line a monthly scheduling plan is currently in use that is developed manually considering the family but not the specific configuration of each machine (set of options is not considered) and individual skills of operators are not considered (the team they belong to is the only information used). Nonetheless, both the production mix and the differential operator's skills have a huge impact on the line performance and, in particular, on the line balancing and the level of saturation of operators that, in turn, influence the generation of possible delays in delivery times.

The simulation considers the number of options and the set of skills of different operators leading in such a way to a more precise and realistic evaluation of the production times. The production plan for the next month (February 2020 at the time the analysis was carried out) has been used to understand how the simulation can support the decision-making process. Differences emerge between the LT provided by the simulation and the LT calculated according to the current approach using average historical data (see **Fig. 3**). On average, the difference is negative (-0.75) meaning that the more precise calculation of the simulation shows that machines are completed in less time than expected, thus providing a more realistic overview of the finished dates. On the other hand, when the difference is positive, it means that the traditional approach underestimates the actual time it takes (this happens when machines have more options or require particular skills) to complete the machines and possible delays can occur. The simulation tool allows the testing of the feasibility of a production plan taking into account aspects that currently are not considered in the analysis.

KN	Assembly Start	Expected End	Expected LT	Simulated LT	Difference
41622	17.02.2020	25.02.2020	7	6	-1
41623	24.01.2020	03.02.2020	7	7	0
41624	28.01.2020	05.02.2020	7	6	-1
41625	07.02.2020	14.02.2020	6	6	0
41636	03.02.2020	10.02.2020	6	6	0
41637	05.02.2020	12.02.2020	6	8	2
AVERAGE			6.34	5.59	-0.75

Fig. 3. Extract from the scheduling plan of the analyzed month showing differences between expected LT with traditional scheduling and simulated LT

Each month, by simply updating an Excel input file, the company can simulate the production plan of the future month obtaining several interesting inputs (delayed machines, production plan lead time, resources utilization rate) and dynamically improve the production scheduling. Timely identifying the critical machines, it is possible to dedicate to them less saturated resources and shorten their lead time.

Interviewing company's experts, it emerged that on average 3 to 5 machines are behind schedule every month on this line. Using simulation, initially they expect to halve the number of delayed machines resulting in a reduction of 25 units the number of delayed machines per year only for the ST line. Considering the products mix and projecting this result to others lines, the expected reduction of total number of delayed machines (from assembly to test area) can arrive to 35-40 machines per year.

5.3 Optimization of the training plan

Delays along the line are often due to lack of operators with the proper set of skills. The time machines spend in a queue is not value-added and needs to be reduced as much as possible. The simulation model has been used to identify for which tasks and operators training is more beneficial in order to reduce queues and, hence, increase the line productivity. Considering again the ST line, a two-month production plan (June and

July 2019) has been analyzed focusing on the total waiting time in each of the work-station due to lack of skilled operators (see **Fig. 4**). Unexpectedly, the main problems are related to the first stations. A matrix has been created where for each operator it is possible to assign up to three skills for each station. The matrix is then used as an input file for the simulation model that can analyze how different training paths impact on the line performance. The definition of the training plan took into consideration some constraints:

- Availability of trainers: for each operator to be trained, an expert operator (trainer) needs to be identified. During training sessions, proper time is needed to transfer the knowledge to the operator.
- Constraints in the training: an operator learns faster if the phases he/she is taught have affinities with those already known. For this reason, defining a plan in advance (without interacting with the line managers) leads to situations that are not feasible.
- System dynamics: given the current logics, it is very difficult to understand if the impact of a proposed solution because of the interactions of lots of elements that generate not predictable results.

	Number of Stops	Average Wait Time	Total Wait Time
ST/01	33.7	153.18	5387.4
ST/02	35.5	161.69	6227.848
ST/03	38.1	155.67	6011.577
ST/04	34.2	149.13	5605.6
ST/05	36.9	140.6	5408.064
ST/06	35	139.96	5557.266
ST/07	35.4	87.33	4403.712
ST/08	36.3	92.4	4058.376
ST/09	37.4	82.52	3504.592
ST/10	37.1	88.75	3492.288
ST/11	38.5	82.54	3851.288
ST/12	36.3	77.63	3353.952
ST/13	38	62.05	2405.104
ST/14	37.5	63.55	2272.704
ST/15	37.6	59.27	2497.435
ST/16	38.3	54.7	2333.616
ST/17	35.8	60.06	2316.666
ST/18	38	63.92	2107.926

Fig. 4. Total waiting time (minutes) due to lack of operators in the single stations of the ST line

Different training plans acting on the set of skills of single operators have been simulated for the same production plan and the resulting waiting time has been recalculated. Improvements have been obtained in terms of average lead time to produce one machine (-2.95%) that is expected to decrease of 1 hour. Over a year, such saving can be used to satisfy the demand of additional 10-15 machines.

In the future, the company's experts can modify the operators' training matrix input file of the simulation model in order to simulate alternative training plans and understand the related impact of production's KPIs, non-value-added times and resources utilization. In the short time, company's managers can identify which operators need to be trained on which phases and quantifying the cost-benefit ratio. This tool is extremely powerful because it allows to understand the impact of each change considering the related dynamics and unexpected impacts.

6 Managerial implications and conclusions

The current availability of data in the production system makes easier the development of simulation models that can supports the decision-making process. In this paper, the simulation model of an assembly line developed in a company producing high precision machines has been presented and its use in three decisional processes leading to performance improvement has been commented. The simulation tool is first of all a mean to assess production KPIs that allows production managers to dynamically monitor the status of the system and take more informed decisions. Alternative uses of the model to the ones already shown can be identified to support further choices in the production system. Though positive results have been already obtained and corrective actions have been implemented accordingly, the model needs to be further developed and fine-tuned. In particular, additional data collection and programming activities are needed to extend the model to include also the test and metrology phases. Furthermore, additional data sets are needed to analyze the probability distribution of process times to increase the reliability of simulation inputs. So far, performance of the proposed model has been assessed against the current approach in use in the company. Further studies should be carried out to analyze the adequateness of other modelling methods such as queuing theory, Markov chains or casual loops diagrams.

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