Abstract: This paper focuses on the reconfiguration and scheduling optimization of a complex Flexible Manufacturing System and proposes a complete methodology from problem statement to analysis and solution definition and assessment. In particular, Discrete Event Simulation (DES) has been used to support decision-making. A complex case study has been carried out in an Italian company, with the aim of assessing the internalization of a production phase and, at the same time, identifying a scheduling algorithm minimizing the total cycle time. In particular, the optimization algorithm has been integrated with the simulation tool providing a direct assessment of the scheduling on the simulated process.

Keywords: simulation, discrete-event systems, flexible manufacturing systems, optimization problem, performance analysis

1. INTRODUCTION

A production system is a complex structure characterized by several rules to follow and different goals to achieve taking into account various constraints set by the environment. Many actors are involved in the design phase and in the production, planning and control activities (Li (2014)).

These systems, during their life, need to continuously adapt to new market requirements, increasing the customization level of the products, reducing cycle time, keeping high quality level at lower costs. In order to achieve these objectives engineers must consider reconfigurability and flexibility aspects in the design phase of the plant. In particular, according to the definition of reconfigurability and flexibility in Wiendahl (2005):

(1) Reconfigurable Manufacturing System (RMS), are systems where plant components (machines, cells, conveyors, etc...) can be added, removed or improved in order to change its behavior to respond to market demand.

(2) Flexible Manufacturing System (FMS), are systems able to yield a wide range of products, that are customization of a single base unit. Usually, this kind of plants is suitable for prototypes and unique goods where high customization is required and low volume is provided.

The trade off between reconfigurability and flexibility is the most relevant challenge that engineers face during plant design, since usually a flexible system is tricky to reconfigure and vice-versa. This paper deals with the reconfiguration and scheduling optimization of a complex Flexible Manufacturing System and aims at proposing a complete methodology from problem statement to analysis and solution that leverage on Discrete Event Simulation (DES). Furthermore, a case study in an Italian company working in the automotive sector has been carried out in order to test and validate the developed methodology. In more detail, the aim of the industrial application is to optimize the production scheduling minimizing the cycle time and the Work in Process (WIP) after the introduction of a painting station in the production process, as shown in Figure 1. To this purpose, Discrete Event Simulation (DES) is used since it allows to implement several what if scenarios and define the best configuration, taking into account the several constraints of a real production system. About that, a deep analysis of the plant is needed, a strong data gathering performed and an intensive simulation activity run. The simulation job will show the key of success in the optimization of production phases schedule that allows to fulfill all the new constraints of production plant.

In the literature there are several works regarding production optimization using DES. A recent collection of 26 manuscripts is provided in Sahu and Pradhan (2016), but most of them focus on a single line or a small production plant. Moreover, the analysis is not as deep as expected. In Choi et al. (2002) a foundry plant is studied and a simulation model is built in order to analyze bottlenecks in the production process. The simulation highlights an occupancy above the 95% of assembly stations which delay the following work phases. The solution adopted by the company is to add a new assembly station. In this
case, the solution adopted is quite simple, there are no changes in the plant morphology and the reconfigurability characteristic of the plant is not tested at all.

In Jacobson et al. (2006) the problem of patients scheduling in health care is considered. The schedule must consider the duration of medical examinations, patient’s caregiver and caregivers commitments themselves. The output is the time table of appointments. The effort expressed in this proposal is focused on optimized human resources in a health care clinics. In this case, with respect to the work proposed in this paper, the function to minimize has not hard constraints like production targets or stocks dimensions.

The work by Spedding and Sun (1999) is focused on costs analysis of a Printed Circuit Board (PCB) manufacturing company, in particular on Activity Based Costing (ABC). The manuscript explains the concepts and the formulas which ABC is based on and shows the simple simulation model built. The work does not highlight in optimization of costs, but in pure estimation of them only.

As above-mentioned, the paper overcome the state of the art since it covers the complete process from problem analysis to problem solution using DES and apply it to a real industrial case. In order to achieve this aim, the paper is organized as follows:

(1) Introduction to the concept of simulation and the tool used in the methodology (i.e. Siemens Plant Simulation)
(2) Problem description and constraints identification
(3) AS-IS model construction and validation
(4) TO-BE scenario with what-if cases
(5) Schedule optimization using MATLAB - Plant Simulation interface

Particular attention will be put on the simulation process and the iterative steps which characterize it.

2. MANUFACTURING PLANT SIMULATION USING DISCRETE EVENT MODELS

Discrete event simulation can help industries to study their production plants and verify their logistics and layout solution before making changes in the plant and stop production without certainty that the choice taken will improve the production process (see Heilala (1999)). DES is a form of computer-based modeling that provides an intuitive and flexible approach to represent complex systems.

This means that physical phenomena which govern the plant must be known, but the equations which represent them should be expressed alternatively from mathematical expressions (Karnon et al. (2012)). In DES, the state of the system changes only during specific time instants defined as events. Simulation can be seen as a list of events ordered by a timestamp where an event can edit the status of the system, add new future events or remove events already scheduled (see Jerry (1984) for more details about DES).

In general, simulation is the representation of a real system using software tools. It wants to imitate the reality providing results according to the simulation goal. To this purpose, the simulation model must reflect data obtained by the production line. In other words, if the model properly represents the system then results will be consistent, otherwise the simulation will not bring benefits.

The following 7 steps provide the best practice in the job of simulation in order to achieve better results with the expected goals (Law (2008)):

1. Determine the goals: goals suggest which areas are the focus (it can be a process or a plant), the precision needed in the results and the necessary data to achieve the success
2. Collect data: in this step is important to analyze the actual system and check out what information are relevant to build the model. Input and output must be identified for each subsystem analyzed. Data gathering is probably the most effort and time-consuming activity in the simulation process
3. Build the model: for this step, the use of a dedicated software tool is needed. The model is an algorithm that manipulates input data according to rules and constraints expressed inside it
4. Validate the model: before simulating and collecting the results, a validation phase is fundamental. This means to verify, through appropriate KPI, if the model behaves close enough respect to the real system. Without this phase, the results are useless. When the model is declared not validate, the process must restart from step 2.
5. Simulate: define a simulation battery and run it on acceptable time horizon. A good choice for time horizon may be at least 10 times the takt time of the process.
6. Analyze the results: results must be critically analyzed to decide whether represent a valid information for the final goal. A negative answer could force the simulation process to restart from step 2
7. Final documentation: as a final step, the documentation report should be filled with the information extracted from the simulation, detailing the necessary improvement applied to the system (unleash constraints, change schedule strategy, etc...)

These iterative steps ensure a correct procedure in a simulation project. Figure 2 shows the loop of simulation process. The industry 4.0 and Internet of Things are providing to enterprises tools which enable data gathering. Data is the first requirement for simulation: step 2 of the list above highlights how data are fundamental. Data are also needed to derive stochastic distributions which generate, during the simulation, events such as failures and scrap randomly.
For example analyzing MTBF and MTTR of a machine is possible to build a stochastic distribution of failures along the simulation.

Nowadays, market offers many tools for simulation. The work proposed in this paper uses Plant Simulation, a software distributed by Siemens for modeling, analyzing, simulating and optimizing production processes and systems, flow of material and logistic operations.

Plant Simulation offers a wide library of preset objects like single process station, parallel process station, load station, conveyor, store, container and so on. The library involves objects for discrete materials, fluids, information flow and optimization tools; the interface allows 2D and 3D models. Moreover, with SimTalk programming language is possible to add code on events or timers which execute operation on the plant. SimTalk, is an Object-Oriented (OO) language with inheritance, polymorphism and hierarchy structure. Every object in the libraries follows the OO paradigm and users can derive new objects coupling and edit properties of the existing one.

This paper focuses on the development and validation of the simulation model. To this purpose, the seven steps of the simulation process have been implemented and described in the following section.

3. DATA COLLECTION AND DATABASE ORGANIZATION

The goal of the paper is to optimize, through DES, the production scheduling of a flexible manufacturing systems producing brake calipers, reconfigured with the addition of a painting phase. Process data have been gathered and the simulation model has been built. The plant subject of this study involves 5 phases:

(1) **Washing.** 7 machines wash calipers with a strong water jet and clean them from smudges placed during the previous production phase. The process can last from 25 seconds per caliper to 1 minute. Usually, in this phase, calipers are worked in pair

(2) **Oxidation.** It is a plant with 13 tanks where calipers grouped on specific frames and moved from a tank to another by a crane system. The process lasts around 1 hour and half

(3) **Cleaning.** This is a manual operation, 7 stations are dedicated to this process that can last from 20 seconds to more than 2 minutes per caliper

(4) **Painting.** It is an external phase where semi-finished calipers are painted. Calipers depart from the company warehouse with an order where the color for each caliper is declared and cannot be changed

(5) **Tampography.** 3 machines stamp the logo on the caliper. This operation takes less than 1 minute per caliper and it is the final phase before the delivery is finalized

Currently, the painting phase is outsourced to a local supplier. This means that the semi-finished products, after the cleaning phase, are loaded on a truck, sent to the provider’s plant, stocked at the provider’s plant, painted and sent back by truck to the company. All these operations increase both the cost and the production time of the brake caliper. Indeed, this process takes around 7 days while the painting time is of only 2 hours and 30 minutes. For this reason, the company is willing to internalize the painting phase through the acquisition of a new painting station. Thus, the company aims at identifying the best layout configuration and the scheduling algorithm that minimize the total caliper cycle time.

As described in Figure 3, the internal flow involves the washing, oxidation, cleaning and tampography phases while the painting phase, before tampography, is performed by a provider. The plant produces 1000 types of caliper every week and each type follows a specific production path, making the production system high flexible in terms of products produced. From process point of view, the main features of the plant are the following:

(1) Every caliper type has an univocal production code
(2) Production codes are grouped in families
(3) There are two types of container where calipers can be placed, caissons and frames. Caissons are generic and do not depend of caliper code, while frames are specific for family of codes. Usually 2 caissons (containing both caliper left and caliper right) of the same model are put in a single frame
(4) Some production codes perform the washing phase integrated with the previous process of die-casting
(5) The oxidation is a chemical process with 3 different recipes which treat a caliper in different ways depending on following color and mechanical features
(6) Only certain caliper types need a process of manual cleaning, this depends on the physical shape of the piece
Painting may not be needed to keep the classic silver color. Tampography can be performed by the provider for those calipers painted at the supplier site.

4. PROCESS CONSTRAINTS AND AS-IS PLANT

Section 3 gave an overview of plant layout and the production process. The as-is model has been built considering the following features:

(1) Although the plant is highly flexible, work cycles are tightly harsh and workers must respect several constraints even though most of operations are performed manually or semi-automatically.

(2) The plant works on 3 shifts of 8 hours each, with 2 breaks of 10 minutes and 1 break of 30 minutes in the middle of the shift. During these breaks, the only phase that work continuously is the oxidation one, while all the other operations need the human operator to be performed.

(3) Normally, during the weekend the plant stops. There may be some exceptions considered in the data analysis but they are not taken into consideration in the following evaluation. Indeed the production target must be reached during the regular working time. Additional shifts in the week-end must be considered only in peak load periods.

(4) The company wants to avoid an intermediate stock of pieces before painting. In this way it will not require to reserve space to stock calipers and logistic department does not need any change in production management. The total investment also involves a new machine for tampography and new frames if necessary.

(5) Production codes are grouped in families. Two production codes belonging to the same family do not need machine setups to be processed, while this is necessary for codes of different families. Moreover, inside a family, left and right calipers of the same car model must be produced consecutively.

(6) Each phase has strict constraints. Cycle times are hard deadlines and are fundamental to reach the production target. The washing phase is fed by a pre-washing store where batches of calipers with the same production code are waiting to be processed.

(7) There are 7 machines for washing, but a caliper type can be worked only on a machine enabled to wash that family, this depends on the programs upload on machines.

(8) There is no automatic schedule that optimizes setup time and machines loads, the schedule is determined by experience and common sense rules. This is a hot topic for the company that find in this process led by experience an obstacle to improve the reconfigurability in front of an high level of flexibility.

(9) After washing, calipers are placed on frames which usually contain left and right calipers of same car model. Frames are necessary for the next phase, the oxidation. Frames are a precious resource, since they are limited in number and specific to contain only certain family codes. When a frame is not available, calipers are stored in caissons waiting for a free frame that can host them. The management of this resources on the plant is important and critical to reach high production volume.

(10) All calipers in the plant pass through the oxidation phase, calipers from washing phase and calipers directly from die-casting process. Here, calipers can be processed with 3 different recipes. The chemical treatment which distinguishes the recipes depends on next process the calipers will undergo on the plant. For this reason frames are organized in families or more strictly in car model codes.

(11) At the moment, consequently to oxidation phase, calipers are removed from frames and placed in caissons and scheduled for cleaning phase if necessary or stored waiting for painting phase and then load on a truck to go to the provider.

(12) The final phase is the tampography. For those calipers which do not undergo the painting phase, they wait for tampography after the cleaning phase; with regard to those calipers which come from external painting phase, some of those received the tampography at the provider, for the other remains unchanged the process of queue in front of tampography machines.

After this process, calipers are now ready to be delivered. Based on the plant information and the constraints reported above, the model has been built using Plant Simulation software. The model respects the features of the plant as-is and the validation has been performed using an history set of input and output data. The results of validation are presented in the next section.

5. SIMULATION AND MODEL VALIDATION

The model has been run and the results validated with the company manager in order to be sure that the model behavior is aligned to reality. The simulation data are based on production target expected for next year, but afterwards, target production will increase of around 5%.

The validation of the model shows a good alignment with the real behavior. Relative squared error (RSE)(see 1) has been used as main indicator to validate the model. Results show an average RSE under 5%, more precisely 4.87%. Only for the washing phase the RSE is less than 0.5%. Furthermore, the graph in Figure 4 represents the comparison between the day by day pieces produced by the company plant (blue line) with the pieces simulated by the model (orange line) (the values are normalized over the biggest one). The same comparison has been done with the output of each phase (Figure 5 shows washing phase output) and the pre-washing stored stock quantity. All these results shows that the simulation model well fits the reality and, then, it can be used as decision making tool for future scenarios.

\[
RSE = \frac{\sum (y_i - \hat{y}_i)^2}{\sum y_i^2}
\]  

(1)

Referring the equation (1), \(y_i\) is the real amount of calipers produced in day \(i\) and \(\hat{y}_i\) is the same value obtained in the simulation environment.

6. ANALYSIS OF THE RESULTS: TO-BE SCENARIO

After model completion and validation, the to-be scenario has been built adding the painting station. In particu-
lar, several what-if cases have been developed, trying to find out the best solution that optimizes the production according to painting system constraints and production target. Figure 6 shows the new production flow including the painting phase inside the factory.

The constraints of the painting plant are:

1. Setup time of 5 minutes every time the family code of processed caliper changes, called technical setup
2. Setup time of 15 minutes every time the color changes, called color setup
3. The takt time of the painting plant is 2 hours and 30 minutes

In order to reach the target production, the painting plant should work at full time with maximum 3 technical setups per shift, 9 per day, and 1 color setup per shift, 3 per day. The company expects to continue its production without introducing any optimized scheduling system and keeping a flow process without intermediate stocks. Beside the target production, an important index to evaluate results is the number of setups according to the constraints listed above. In total, 30 scenarios are run to verify the to-be plant layout, varying the following parameters:

1. The number of frames: they are changed to verify improvement increasing some of them
2. Working shifts: they can be extended in the week-end for every phase independently
3. Input production planning
4. Washing machines compatibility: it can be added to simulate update in machine programs

Considering the constraints explained above and analyzing the type of orders the plant performs, the current scheduling of the washing phase resulted to be inadequate because it is led only by production code without taking into consideration colors which calipers will be painted. In fact there are 16 different colors and 15 possible color setups, this means that some colors must be performed every 2 weeks and moreover calipers painted of the same color must be washed consecutively. In this way, the painting phase exploits technical setups, which are more available than color ones. This led to the conclusion that washing schedule should be forced to be programmed every 2 weeks with a frozen zone of 24 hours. One more condition is that caliper color must be chosen before wash.

The features of this washing schedule are:

1. Group calipers by color and subsequently by code
2. Spread batches on more washing machines as possible
3. Ensure all batches washed are on frames before painting calipers of different color
4. If possible, start new color with the last code performed, this save a setup in both washing and painting phase

Furthermore, the painting phase processes calipers of the same color until all active orders of that color are finalized.

The last step of the presented work is to dynamically schedule washing machines to avoid delays due to machines failures. Based on the what-if case schedule, exploiting MATLAB Optimization Toolbox, a first rudimentary algorithm is tested.

7. SCHEDULING OPTIMIZATION

A first attempt for deploying a schedule algorithm has been made using MATLAB Optimization Toolbox. Plant Simulation COMs allows MATLAB to monitor the status of Plant Simulation model during its run. Analyzing the batches stored and the current batch processed in washing phase, MATLAB calculates and communicates to Plant Simulation model the schedule for the day.

To properly resolve the problem of scheduling, the best optimization method in the MATLAB Toolbox is fmincon which finds the minimum of the constrained nonlinear multivariable function. The goal is to minimize the maximum processing time in washing phase respecting the store inventory.

The fmincon method, see equation (3), take as parameters:

1. The function to minimize, in this case it is the maximum punctual product from the sum of time of processing respect the quantity stored and the input to optimize, see (2)
2. The initial condition which is the input to optimize at the first iteration
3. The constraints which specify the compatibility between washing machine and caliper family

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Furthermore, the painting phase processes calipers of the same color until all active orders of that color are finalized.

The last step of the presented work is to dynamically schedule washing machines to avoid delays due to machines failures. Based on the what-if case schedule, exploiting MATLAB Optimization Toolbox, a first rudimentary algorithm is tested.
Equation (2) calculates the highest processing time of washing machines. In this way the \textit{fmincon} method can minimize this time and the result is the schedule to apply, compliant with constraint, to equilibrate the load on washing machines. In particular, in equation (2), $u$ is the input on which the function $J$ is minimized and $A$ is a fixed parameter during the optimization, but variable for each schedule calculation. The result of the product between $u$ and $A$ is a matrix \textit{machinesNumber}x1 containing the total processing time of the scheduling for each machine.

$$J = \max(uA)$$

$$u = \text{matrix}[\text{machinesNumber, caliperCodesNumber}]$$

$$A = \text{matrix}[\text{caliperCodesNumber, 1}]$$

Then, equation (3) returns the input value for the minimized total processing time or rather the schedule of the washing phase. In the scheduling matrix, crossing caliper codes (column) and machines (row) it is visible the portion of batch to process on there.

$$\text{schedule} = \text{fmincon}(\max(uA), u_0, \text{cons})$$

$$u_0 = \text{matrix}[\text{machinesNumber, caliperCodesNumber}]$$

$$\text{cons} = \text{matrix}[1, \text{numberOfConstraints}]$$

This operation is made every simulated day: the simulation model stops and allows MATLAB script to catch inventory values and create the matrix $A$ multiplying them with processing time of single caliper selected by code. After resolving \textit{fmincon} method, MATLAB writes the schedule in Plant Simulation model and restarts the simulation until the next day.

This is only a first attempt which provides a schedule optimization in ideal condition, without taking into consideration machine failures nor in the constraints nor in the function.

8. RESULTS

The high setup cost of painting phase would force the company to change its scheduling logic, giving higher priority to the colors, while the previous phases focus on code model. Furthermore, although the company expected to keep a flow production in the painting phase, this would not be possible because of the amount of different codes and colors the company produces. This flexibility in production would cost a small stock of calipers before painting of around 2500 pieces or better one day of production. However, the introduction of this phase would introduce several advantages in managing customer’s orders, first of all a reduction of delivery time and also very important the reduction of the frozen zone in orders schedule. Along the several what-if scenario performed, the effort has been mainly focused on the scheduling strategy before the washing and painting phases, due to a incompatibility between the two in the optimization of working time. In more detail, as already explained in the paper, the most costly setup in the washing and painting systems are based on different caliper features: the washing phase setup is made when caliper code changes, while in the painting phase is it made when the color changes. Despite that, the prefixed production target is reached, nevertheless a further increment of the number of colors may flow in a change of plant specification to keep the same production target.

9. CONCLUSION

In conclusion, this paper reported a complex case study related to the reconfiguration of a flexible manufacturing system, providing a complete description of the process of plant analysis. The process involved is structured as follows:

1. Plant analysis and constraints identification
2. Construction of the simulation model and validation of it
3. TO-BE scenario and what-if cases
4. Schedule optimization with MATLAB

This model will lay the foundation to the development of the digital twin of the production system that, taking real time data directly from the production machines, will support the plant manager in taking decisions related to day by day scheduling. Before that, the next steps will be to refine the scheduling algorithm and test it on the current production system.

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