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A Methodology to Support Manufacturing System Design Using Digital Models and Simulations: An Automotive Supplier Case Study

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Abstract: Emerging tools for digital manufacturing support the decision making during the design of production systems. Simulations have proved to enhance the plant design process by generating accurate predictions allowing the evaluation of different alternatives. However, the use of these tools needs to be guided to achieve an efficient decision-making process. Therefore, this paper proposes a methodology to guide the engineering efforts towards plant design and operation using discrete event simulation tools. The methodology integrates all essential activities to develop, optimize, and validate the plant. The presented methodology aims at specifying the approach taken to generate the technology viewpoint from the Sensing, Smart and Sustainable Enterprise Reference Model (S^3E-RM) which allows the integrated manufacturing enterprise design. A case study is presented to demonstrate the results obtained when using the methodology. The case study is a plant from a Tier One Automotive Supplier that produces plastic and metal parts. The advantages and limitations of the proposed methodology are visualized in the case study implementation and then discussed in the conclusions.

Keywords: Discrete Event Simulation, Formalisms and Modeling Techniques, Manufacturing Resources and Processes, Plant Design and Optimization

1. INTRODUCTION

Today manufacturing enterprises need to be designed as sensing, smart and sustainable (S^3) [Weichhart et al. 2016]. S^3 enterprises are continuously monitoring their context and operation (sensing); they can take smart decisions creating collaborative networks that enhance their reactive and proactive capabilities (smart); and they use their technological and human resources to become sustainable in the economic, social, and environmental senses. This vision of an enterprise is becoming a reality due to the convergence of technologies such as networks, mobility, big data analytics, cloud computing and cyber-physical systems. More and more industries are adopting smart sensors in their operation to obtain real-time data, providing insight from the diverse context that enables a knowledge-based decision making. Additionally, governments are pushing to achieve sustainable development in the manufacturing sector.

The recent Paris agreement [United Nations 2015] is an example of the multiple efforts to mitigate the environmental impact in the industry. In manufacturing specifically, green and sustainable manufacturing have been created as new paradigms to lead the manufacturing towards sustainability [Esmaeilian 2016]. As a result, being Sensing, Smart and Sustainable is becoming a necessity to be competitive in the digital era.

The S^3 Enterprise Reference Model (S^3E-RM) and methodology [Chavarría-Barrientos et al. 2017] offers an integrated approach to design S^3 manufacturing enterprises. This reference model helps in identifying the enterprise requirements that support the concepts of Sensing, Smart and Sustainable.

The S^3E-RM guides the design planning and implementation of the enterprise system and organize the implementation process to evolve the enterprise towards the desired level of automation and integration.

The use of five viewpoints organized in a top-down manner. These viewpoints (enterprise, information, computation, engineering and technology) are used to direct the design efforts on different aspects of a manufacturing organization. The top-level viewpoint (enterprise viewpoint) focuses on the definition of the business concept while the bottom level viewpoint (technology viewpoint) provides the technological resources needed for the enterprise operation.

The technology viewpoint is about selecting the technology needed by the enterprise to operate. Hence, this viewpoint supports the implementation phase of the enterprise. Lifecycle. In that sense, it is important to consider life-cycle elements (such as manufacturability, operability, availability, maintainability) of the manufacturing system during the design process. Negahban and Smith [2014] showed that discrete event simulation is an effective tool to assist the plant design and operation. However, they recognized that there is still a need for more efficient techniques to deal with the complexity of manufacturing systems.

Therefore, this paper proposes a methodology to guide the development and improve the decision-making process. The methodology can be used as the technology viewpoint of the S^3E-RM to assist the plant design and operation using simulations. Section 2 presents the methodology. In section 3, the application of the methodology to a tier one automotive supplier company is described to test and validate the efficiency of the proposal. Finally, using this experience, some advantages and limitations are stated.

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2. THE METHODOLOGY

The proposed methodology fits in the technology viewpoint of the Sensing, Smart and Sustainable Enterprise Reference Model (S^3E-RM) [Chavarría-Barrientos et al. 2017].

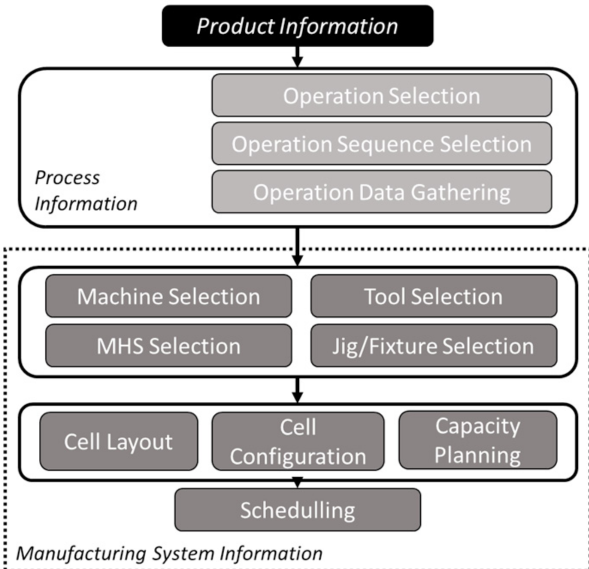

Fig. 1. Enterprise planning activities.

The first step is to define the enterprise planning activity. In the proposed methodology, a reference set of enterprise planning activities is proposed according to the methodology for manufacturing system design proposed in Molina and Bell [1999].

As it can be seen in Fig. 1, the focus in this paper is on manufacturing system development including enterprise planning activities such as machine selection, layout and scheduling. However, some enterprise planning activities related to product and process development can be considered too.

The proposed enterprise planning activities follow a lifecycle approach. After selecting the enterprise planning activity, the action-research cycle [Kemmis and McTaggart 1988] is used to guide the design and modelling activities. Action research follows a spiral process that starts as a cycle of planning, action, observation, and reflection, where the reflection phase triggers further cycles of planning, acting, observing, and reflecting.

To elaborate the action-research phases, three existing methodologies were considered. Firstly, the VDI 3633 industry standard for simulations and optimization was used as a guideline for the manufacturing-system model development (Fig. 2).

Secondly, the methodology developed by Molina and Medina [2003] suggested that different model updates may be necessary along the modelling process. The methodology steps are shown in Fig 3.

Last, the methodology of Sage and Rose [1999] provided additional elements for an incremental and evolutionary development of the life-cycle process. Similar to action-research, Sage & Rose's methodology is composed of connected cycles, each composed of formulation, analysis, and interpretation activities.

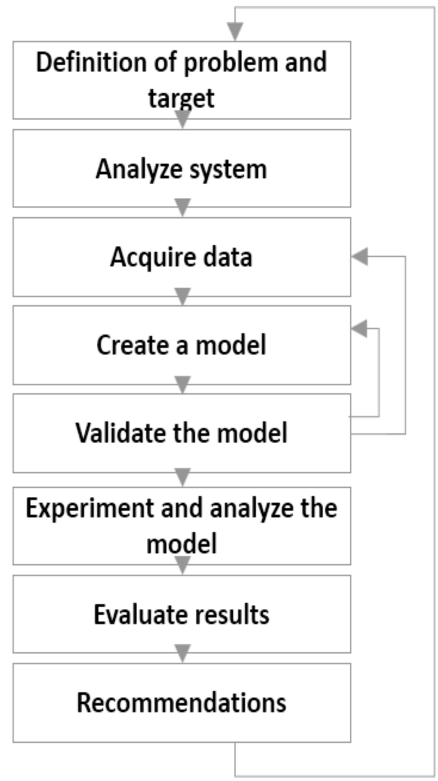

Fig. 2. Steps for using models and simulations as stated by the VDI 3633 Industry standard.

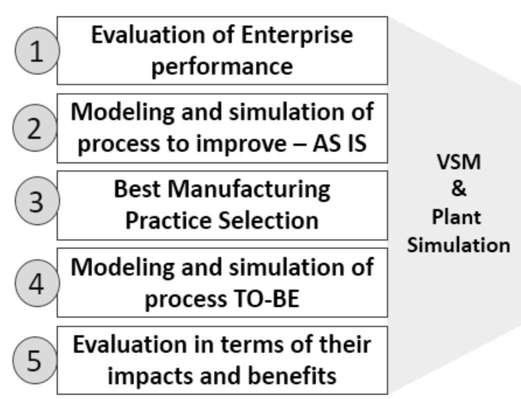

Fig. 3. Methodology for evaluation of best manufacturing practices [Molina and Medina 2000].

Accordingly, the activities done at each action-research cycle become as follows:

- Plan: (1) define problem and target according to the set of enterprise planning activities, (2) establish a set of objectives (3) specify the decision criteria for analyzing the alternatives (objective measures), and

(4) propose one or more alternatives of the manufacturing system.

- Act: (1) Determine the type of model according to a model typology, (2) Develop a model and validate it. Carry experimentation if necessary.
- Observe: (1) simulate the model and (2) evaluate the objective measures.
- Reflect: (1) Identify one or more courses of action according to the results of the *observe* step and restart the cycle if necessary.

The model typology offers a classification of models for a more effective model selection, which depends on the type of application. The typology of models is based on the level of complexity of the models. The proposed typology includes three types of models: black-box model, operation model and integrated operating model.

The objective of the *black-box model* (See Fig. 4) is to identify and to represent the main activities of a process and the interaction between them. Several activities can be grouped within a single operation, to maintain a simplified process model. A black box is created for each activity that is involved in a process.

The simplified level of detail allows us to have a preliminary estimation of the productive capacity of the integrated activities of the process. Scenarios with this level of detail can be found in Siderska [2016] and Kliment [2014]. Aspects such as layout configuration, operator actions, material transport, and operating strategies are not considered.

An *Operation Model* (See Fig. 5), is a building block for creating an integrated model of operations. This level of detail is suitable for modelling a specific activity, a workstation or a small process [Musil, 2016; Borojevic, 2009; and Malega, 2014].

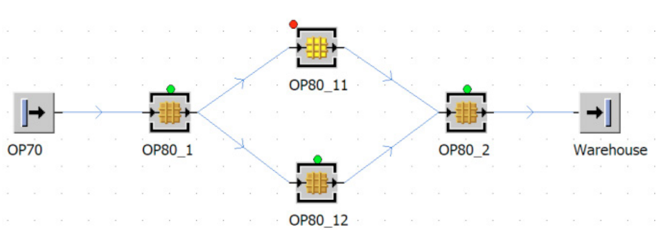

Fig. 4. Black-box Model for a manufacturing operation.

The maximum productive capacity of the activity or small process is analyzed. This model considers that the input of the material is always available and the output material of the system can be processed at any time. “What-If” scenarios can be evaluated to determine modes of operation of the activity, the number of operators and transports that intervene in the activity or process.

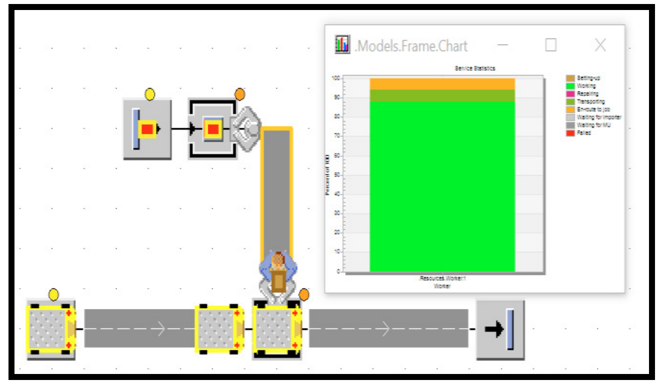

Fig. 5. Operation Model for an automotive assembly line.

The Integrated Operation Model (See Fig. 6) is useful for modelling the whole manufacturing system. An integrated operation model consists of interconnected operation models. This model is based on the material exchanges and operation connectivity information that were defined in the black box model.

The integrated operation model can be used to evaluate scenarios in which the variables of the individual processes interact with each other.

Therefore, it becomes possible to evaluate objective measures in terms of bottlenecks, idle times in loading and unloading processes, etc. Furthermore, in the *reflect* step the modifications to the manufacturing system can be done because the evaluation in the *observe* step is holistic. Modifications of the manufacturing system can range from adding operators to modifying the layout of the machines.

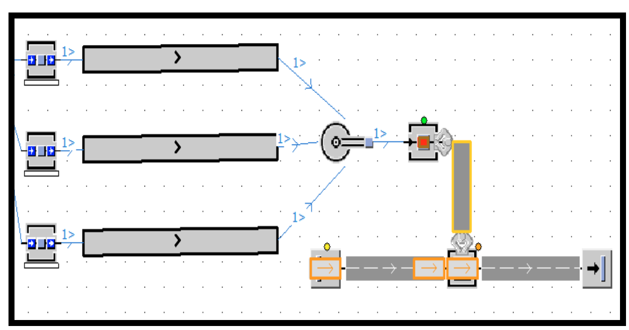

Fig. 6. Interconnected Operation Models to produce an Integrated Operation Model

3. AUTOMOTIVE SUPPLIER CASE STUDY

The application of the proposed methodology has been done in a multinational company, an original equipment manufacturer tier one automotive supplier of metal and plastic parts. The methodology is applied to design a manufacturing system of a new product to be manufactured at a new plant in the Bajio region in Mexico. The company is looking for the best performance and efficiency of the production lines using already specified equipment. The manufacturing system is being designed to achieve the capacity of up to 500,000 parts per year. Several discrete event simulations were carried out to evaluate the design and propose modifications.

In the following examples, the enterprise planning activities, the methodology and the typology have been applied. Part of the data is not included in this paper due to a confidentiality agreement between the researchers and the automotive manufacturer. However, the main results are presented as well as the procedure and activities followed to improve and design the plant.

3.1 Example 1: worker strategy

Plan: The objective is to determine the best operator loading and unloading strategies for a group of six CNC machines, where two operators load and unload parts. One operator is responsible for loading and unloading material of three machines. The selected objective measures are productivity, availability, percent of working time. The estimation of availability and percent of working time were based on the calculation of: percent of load time, percent of unloading time, unload waiting time, load waiting time, processing time, and downtime. The loading and unloading times of material were obtained from a similar process, in a manufacturing facility which belonged to the same company. Other data included the frequency of machine failures occurred and the mean time to recovery (MTTR). The distance travelled by the operators in the corridors and the distance between machines were obtained from the layout (See Fig. 7).

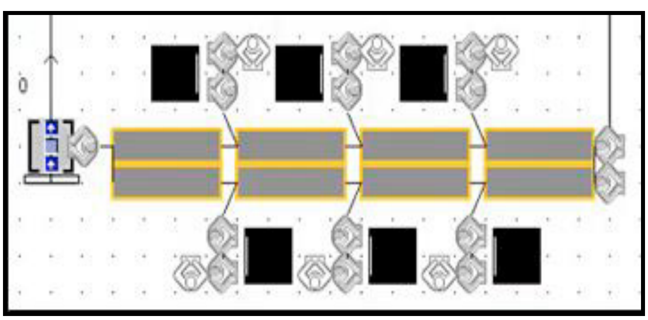

Fig.7. Operation Model for loading and unloading materials in numeric control machines.

Act: An operation model was developed for the CNC machines section. In the first iteration of the action-research cycle, the operator strategy was to load or unload the machine that is closer to the operator. In further iterations, a new three additional operator strategies were analyzed: (1) The operator follows a pre-established order to load and unload the machines, (2) Machines are synchronized to finish an operation at the same time. The operator unloads the parts after all the machines finished their jobs, and (3) The operator is presented with an estimation of the time to completion for each machine and unloads the machine with shorter time to completion.

Observe: A preliminary simulation was carried out for the original operator strategy, in which the operator loads the machine that is closer to him. As a result, it was confirmed that necessary part production could be achieved but operator efficiency was below the minimum allowable limit. In subsequent iterations of the action-research cycle, simulations were carried out for each of the additional operator strategies.

All the simulations assumed that raw material was always available and the output material was always processed without delay. Simulations included the effects of stochastic failure events. For all strategies, a 12% downtime is considered.

As shown in Table 1, a comparison was made between the four different strategies. The results indicate that strategy 4 resulted in better performance in terms of the objective measures.

Strategy	Productivity (parts per week)	Productivity (percentage)	Downtime (percentage)
Company Strategy	10738	60	12
Strategy 1	10390	62	12
Strategy 2	6634	58	12
Strategy 3	13767	72	12

Table 1. Results of using different worker strategies for loading and unloading of material.

Reflect: From the results obtained in the *observe* step, the best strategy is strategy 4. It was decided that the future plant will implement that strategy. The data obtained from the actual plant will be used as to adjust the model and make improvements if necessary.

3.2 Example 2: Optimal number of pallets

Plan: Material handling in the new plant will be carried out by operators and through an automatic conveyor system. The system is composed of two workstations each having an automatic conveyor. An operator transfers each pallet from workstation WS1 to workstation WS2. The objective is to calculate a number of pallets in each workstation. The objective measure is to maximize the productivity in terms of number of parts produced per week.

The initial number of pallets was estimated by the company as 25 pallets for WS1 and 30 pallets for WS2. If the pallet number of WS1 were below the optimum, productivity in WS2 would be reduced, due to insufficient material supply and longer waiting times. Conversely, a number of pallets in WS1 greater than the optimum would create a bottleneck in the automated operation due to an excessive supply of material and the process will be unable to process the material in a standard time.

Act: An operation model was developed to simulate the behaviour of each workstation. For the model development, data were obtained from a similar process in an existing factory owned by the company, and from supplier datasheets.

The model considers productive and non-productive times of the machinery, times for loading and unloading, the frequency of failures of machinery and conveyors, length of transport systems, interconnection times between conveyors, conveyor speed, and conveyor capacity.

The model was validated by comparison with the existing workstations and expert opinion. Because the production rate of WS1 is faster than WS2, determining the optimum number pallets requires the analysis of the whole system composed of the two workstations. Therefore, an integration model was developed by interconnecting the corresponding operation models.

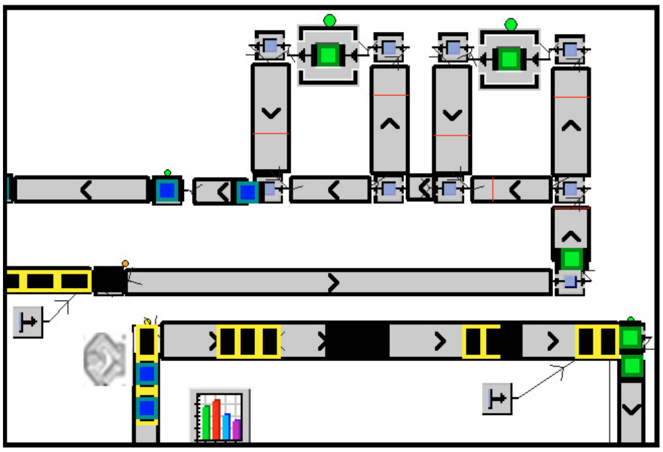

Fig. 9. Integrated Model for two automated operations.

Observe: Combinatorial experiments were generated by defining the lower and upper level[1] of the number of pallets for each of the workstations and a different number of pallets. The difference between the productivity of WS1 and WS2 is due to the difference in cycle times.

Fig. 10 shows the relationship between the number of pallets (experiments) and the number of parts produced. The optimal number of pallets was found to be 25 pallets for WS1 and 40 pallets for WS2 (experiment 2).

Reflect: Compared to the initial estimate, the optimal number of pallets represents an increment of 40 additional parts per week. The change will be implemented once the supplier finishes setting the operation logic of the conveyors.

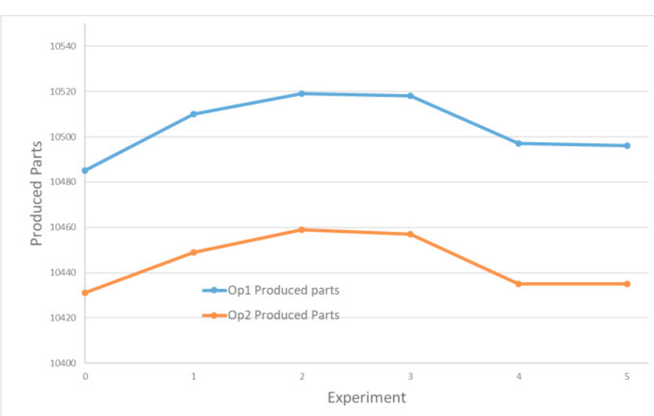

Fig. 10. The number of parts produced for each experiment.

[1] The ratio of cycle times of both workstations suggested that an upper level of 40 pallets.

EXP	Pallets	WS1 Produced parts	WS2 Produced Parts
0	WS1 Pallets: 25 WS2 Pallets: 30	10485	10431
1	WS1 Pallets: 20 WS2 Pallets: 40	10510	10449
2	WS1 Pallets: 25 WS2 Pallets: 40	10519	10459
3	WS1 Pallets: 27 WS2 Pallets: 40	10518	10457
4	WS1 Pallets: 30 WS2 Pallets: 40	10497	10435
5	WS1 Pallets: 32 WS2 Pallets: 40	10496	10435

Table 2. Experiments with different pallet number combinations and the proposed combination by the engineering department.

5. CONCLUSIONS

A methodology for manufacturing system development based on model development was described in this research. The methodology is based on the action-research cycles and several other methodologies. The examples used in this paper focused on discrete simulation models. However, this methodology may be used for other types of models such as differential equation models or agent-based simulation.

The proposed methodology is exemplified by an industrial case study. According to the business directors, the work done have provided insight into the design that allows a better plant development.

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