Discrete Event Simulation to generate Requirements Specification for Sustainable Manufacturing Systems Design

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ABSTRACT

A sustainable manufacturing systems design using processes, methodologies, and technologies that are energy efficient and environmental friendly is desirable and essential for sustainable development of products and services. Efforts must be made to create and maintain such sustainable manufacturing systems. Discrete Event Simulation (DES) in combination with Life Cycle Assessment (LCA) system can be utilized to evaluate a manufacturing system performance taking into account environmental measures before actual construction or use of the manufacturing system. In this paper, we present a case study to show how DES can be utilized to generate requirements specification for manufacturing systems in the early stages of the design phase. Requirement specification denotes the description of the behavior of the system to be developed. The case study incorporates use of LCA data in combination with DES. Data for the model in the case study is partly provided through the format supported by the Core Manufacturing Simulation Data (CMSD) standardization effort. The case study develops a prototype paint shop model, and incorporates alternate decisions on energy use, choice of machines, and environmental bottleneck detection. The study results indicate the potential use of utilizing DES in combination with LCA data to generate requirements specification for designing sustainable manufacturing systems.

Categories and Subject Descriptors

J.6 [**Computer Applications**]: COMPUTER-AIDED ENGINEERING – *Computer-aided manufacturing (CAM)*

General Terms

Management, Measurement, Performance, Design, Economics, Experimentation, Standardization.

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Keywords

Discrete Event Simulation, Life Cycle Assessment, Design for Sustainability, Manufacturing System Design, Standardization

1. INTRODUCTION

Requirements specification plays a vital part during design reviews when designing sustainable manufacturing systems. DES can be potentially used to generate requirements specification after considering what-if scenarios and analyzing alternative models to reflect how a system performs in implementation. This paper discusses how sustainability factors can be incorporated in defining requirements specification using DES to provide decision support for a more sustainable environment and society.

The paper is organized as follows: Section 2 presents a state of the art on DES. LCA as a measurement tool in the context of DES is described in Section 3. Section 4 presents a case study using an automotive paint shop facility example to demonstrate how DES in combination with LCA can be used. Section 5 provides discussions and conclusions as to how the presented case study can be generalized and used for decision support and requirements specification for a sustainable manufacturing systems design.

2. DISCRETE EVENT SIMULATION

Simulation has been demonstrated to be a very effective approach for problem solving and optimizing manufacturing systems design. One of the primary application areas for modeling and simulation is manufacturing system, according to Law and McComas [1]. However, analysis and optimization of multiple objectives is not very common in manufacturing simulation. Detailed discussion of modeling and simulation can be found in numerous books, among the best known are Banks et al. [2], and Law and Kelton [3]. The technology of utilizing DES has been rapidly evolving, hundreds of academic publications and new software features are released every year. DES software and languages have been used for numerous purposes, such as patient flows in healthcare, military strategies, logistics, call centers, restaurants, etc. One of the most frequently stated objectives in DES is profit optimization, i.e., analyzing which of the alternative solutions is the most profitable over time. There are many other criteria, which one could measure with DES. In the past, the emphasis has been mainly on profitability. However, environmental considerations are becoming more relevant and require greater attention as long as humans continue to utilize natural resources. DES and LCA is one possible combination for analyzing the cause and effect of various scenarios where time, resources, place, and randomness of input variables affect the outcome in sustainable manufacturing design. This analysis is an unexplored area; only a few research publications exist. The few examples include: Solding and Petku [4] and Solding and Thollander [5] both describe how DES could be utilized to reduce electricity consumption for foundries. Östergren et al. [6] and Johansson et al. [7] describe how DES could be utilized in combination with LCA for decreasing environmental impacts during food production.

3. LIFE CYCLE ASSESSMENT FOR DISCRETE EVENT SIMULATION

LCA is a methodology for evaluating the environmental impact associated with a product during its life cycle. LCA can be accomplished by identifying and quantitatively describing a product's requirements for energy and materials, and the emissions and waste released to the environment. A product under study is followed from the initial extraction and processing of raw materials through manufacturing, distribution, and use, to final disposal, including the transports involved, i.e., its entire lifecycle. LCA is an ISO standardized tool [8-10].

Using LCA data in a DES model is a novel multidisciplinary technique, which enables environmental impact evaluations of the manufacturing system performance. To the best of our knowledge, only three models of real world systems have been built so far, which utilizes LCA data in a DES model. We discuss one such system in the paper. The other systems were developed for simulating a factory which produces sausages [6, 11, and a dairy, which produces cultured dairy products [12].

4. CASE STUDY

To demonstrate a manufacturing planning scenario with an emphasis on sustainability a simulation model has been built based on the work flow schematic as shown in Figure 1. This scenario presents a paint shop with six painting steps to set the scene for requirements specification in an automotive paint shop.

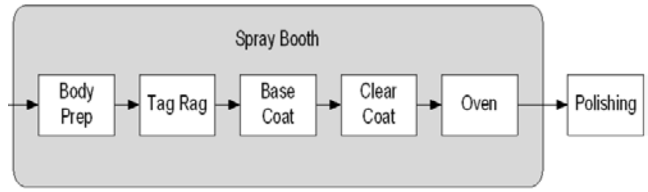

Figure 1. Example of paint shop processes [13]

Figure 1 shows six steps (Body Preparation, Tag Rag, Base Coat, Clear Coat, Oven and Polishing) incorporated in the simulation model. The model was created based on some earlier work [14-17] as seen in Figure 2.

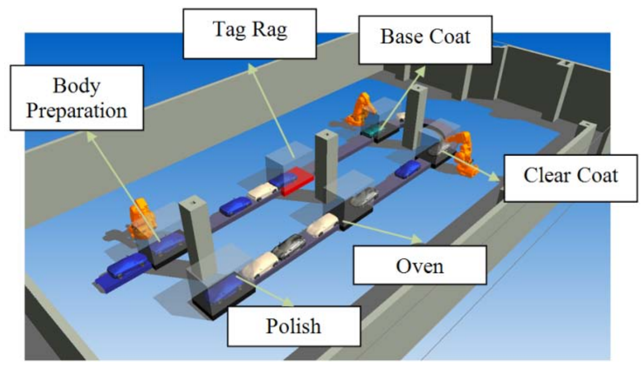

Figure 2. 3D-representation of the paint shop test model

Table 1. Default settings for resources in the paint shop

Resource	Body Prep	Tag Rag	Base Coat	Clear Coat	Oven	Polish
Processing Times						
Cycle time (Normal distribution)	n	n	n	n	n	n
mean (Seconds)	120	130	140	130	240	125
Standard deviation	2	4	1	3	2	1
Energy (kW)						
Down	1	1	1	1	1	1
Idle	5	4	50	50	1800	50
Busy	20	18	500	500	1800	200
Failures						
MTTF (Uniform distribution)	u	u	u	u	u	u
Min (Seconds)	1000	1200	1000	900	1000	900
Max (Seconds)	5000	5200	11000	10900	15000	4900
MTTR (Normal distribution)	n	n	n	n	n	n
Mean (Seconds)	240	260	600	590	1000	240
Standard deviation	2	3	2	3	2	3

4.1 Input data

Each production step has a setting for the resource to be down, idle, or busy. Down means disconnected from the power provider, i.e., no electricity is used. Idle means that the resource is on standby, i.e., some electricity is used. Busy means doing the work cycle as such, i.e., electricity is used. Table 1 shows the input data specifying the energy use from the default settings in the paint shop model, as well as other data needed for setting parameters at the resources of the model such as cycle times, MTTF (Mean Time To Failure), MTTR (Mean Time To Repair), etc.

The data herein presented are for the purposes of demonstration of our scenario and do not necessarily imply an actual paint shop data.

4.2 Problem description

When designing a new manufacturing system certain production goals and economic measures need to be fulfilled. For example the production capacity is specified to be at least a certain level, the cost of the manufacturing system needs to be within the budget, and the environmental impact is expected to be below a certain guideline value.

4.3 Goal

In this case study, the goals of the sustainable manufacturing system are assumed as follows: 1. to reach a production capacity of at least 50000 cars per year, 2. there will be no more than 500 metric tons of CO_2 emission per year, and 3. no new investment in equipment for the existing factory. The current factory is represented by the input data in Table 1, as well as the output data from Trial run 1 in Table 2.

4.4 Experiments

In this case study, the number of input variables are simplified to only a few choices as shown in Table 2. In a real world application however, a variety of designed operating parameters are considered based on the required system throughput. In the experiments, the number of input data parameters can be varied more extensively and practically anything feasible for a real world change could be varied if necessary to bring forth sound requirements specification for the considered manufacturing system.

From the initial settings (Trial run 1 in Table 2), the oven had been identified to be the bottleneck in terms of utilization as well as energy consumption. Some trial runs were performed based on different parameter settings. The settings included the energy source, oven cycle time, and energy consumption as well as a single or two ovens in parallel. The energy sources in the parameter setting included wind, water, or a mix of energy sources depending on the country where the factory is located.

The primary purpose of this simulation is to provide requirements specification support data, and hence also provide support towards designing a sustainable paint shop. In line with this effort, some examples of measures are provided in terms of energy, throughput and CO_2 based on the simulation runs. In Table 2, from the twelve trial runs one can identify the bottlenecks, energy consumption and CO_2 emissions due to energy type used in the paint shop. The results presented in Table 2 are calculated by running the simulation model. The model incorporates lifecycle assessment data from an European Union LCA database as described in Heilala et al. [14].

4.5 Results

Following are examples of conclusions arrived from looking at Table 2:

- The initial setting gives the lowest energy consumption per produced car, as well as trial 3 and 5
- The Oven is the throughput bottleneck initially (trial 1)
- Decreasing cycle time for the oven with 60 seconds does increase output of cars; however Oven is still the bottleneck.
- By adding another parallel oven, the Base Coat will be the bottleneck.
- Wind powered paint shop gives the lowest CO_2 emissions (from energy) per car produced.

Note that these conclusions are not the only items to consider, however they give more information needed and provide for a better decision space that a normal non-discrete event simulation analysis does.

Table 2. An example result of twelve simulation runs

	Input parameter changed			Output data from the simulation run					
					Total per year			Total per car	
Trial run	Oven cycle time and energy use changed to 180 sec and 2400 kW	Energy source type used in factory	Number of parallel Ovens	Utilization Bottleneck	Throughput	Energy MWh	CO_2 Tons	Energy kWh	CO_2 kg
1	1	1	1	Oven	36556	3121,72	1744,6	85,4	47,72
2	2	1	1	Oven	46620	4811,60	2689,0	103,2	57,68
3	1	2	1	Oven	36556	3121,72	19,0	85,4	0,52
4	2	2	1	Oven	46620	4811,60	29,3	103,2	0,63
5	1	3	1	Oven	36556	3121,72	75,9	85,4	2,08
6	2	3	1	Oven	46620	4811,60	116,9	103,2	2,51
7	1	1	2	Base Coat	53280	5458,83	3050,7	102,5	57,26
8	2	1	2	Base Coat	53280	5471,21	3057,7	102,7	57,39
9	1	2	2	Base Coat	53280	5458,83	33,2	102,5	0,62
10	2	2	2	Base Coat	53280	5471,21	33,3	102,7	0,63
11	1	3	2	Base Coat	53280	5458,83	132,6	102,5	2,49
12	2	3	2	Base Coat	53280	5471,21	132,9	102,7	2,50

The left side of Table 2 shows the input data which is varied for the twelve runs. Column one on “Input parameter changed” can be set to either 1 for normal conditions or 2 for 180 sec cycle time and 2400kWh. Column two shows which type of energy is used, 1 for an average country energy (i.e. mixed sources), 2 for wind power, 3 for water power. Column three shows the number of parallel ovens used in the model.

4.6 Discussions

The study results and output data are shown in Table 2. Constraints from the stated goals of the study have to be considered while analyzing the study results. To satisfy the goal to produce at least 50000 cars per year, Table 2 output data shows that trial runs 7-12 are feasible, however an investment in another oven will need to be added to the process. The next goal is to decrease the CO_2 emissions to less than 500 metric tons per year. To reach this goal, standard fossil fuel energy cannot be used. Alternatively wind or water powered energy will need to be used. Table 2 shows trial runs 9-12 as feasible solutions with the use of “green” energy alternatives. In order to minimize the investment goal, the cycle time and energy consumption of the oven does not need to be changed. This means trial run 9 or 11 will be the preferred choice, depending on the energy cost from the power provider. It may be worthwhile to notice that the wind power could be a better choice than the water powered energy alternative in terms of CO_2 emissions.

5 CONCLUSION

The study demonstrated that using the environmental measures from a LCA database and traditional input data with cycle time, disturbance data, etc. for discrete event simulation, new output measures from the model can be used to identify and analyze sustainable manufacturing system design and measures such as energy consumption at the aggregated shop floor level, resource level, and production throughput. Such analysis can also be useful in identifying the bottlenecks on any environmental measure; in this case the energy consumption and carbon footprint in relation to energy source used.

The software used for building and evaluating this model was developed under the SIMTER project as described in Heilala et al. [14], Lind et al. [15], Lind et al. [16] and Johansson et al. [17]. To our knowledge, this software solution is the first effort on combining lifecycle assessment data directly into the discrete event simulation engine.

6 FUTURE RESEARCH

Based on the described case study it would be desirable to be able to represent sustainability related data in a neutral format. One possible solution is to store and use sustainability and other related data for discrete event simulation through the CMSD (Core Manufacturing Simulation Data) specification [19], developed under Simulation Interoperability Standards Organization (SISO) [18, 19]. This will allow us to maintain neutral and accessible measures for sustainability data.

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8 DISCLAIMER

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