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INCORPORATING ENVIRONMENTAL ISSUES IN A FILAMENT WINDING COMPOSITE MANUFACTURING SYSTEM SIMULATION

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ABSTRACT

This paper presents SimBuilder, a simulation system incorporating environmental and quality concerns into a traditional manufacturing simulation environment. These simulations can be used to generate a complete material balance around a particular manufacturing process and can be made available to design engineers to aid in life cycle design assessments. An example developed for the filament-winding composite manufacturing industry is presented.

1 INTRODUCTION

Many manufacturing simulations are narrowly focused on the production aspects of the system. However the flow of discrete parts and assemblies is often only part of the story. Of increasing importance are environmental and cost considerations that depend upon by-products of the process. For instance, many manufacturing operations have solvent and other environmental wastes as by-products of the manufacturing process; their direct and indirect costs (e.g., hazardous disposal and containment costs) have a large impact on the overall viability and cost of manufacturing. If these issues are to be considered during systems design and/or modification, then manufacturing simulations must be expanded to include these factors. Unfortunately a review of the available simulation literature reveals a dearth of material on the subject. There are few references in the published literature which present manufacturing simulations that incorporate environmental issues and/or parameters in the modeling paradigm. This must be done if we are ever to gain a life-cycle perspective regarding our product and process designs.

This paper will briefly review a methodology for incorporating environmental issues into a manufacturing simulation and demonstrate its implementation by presenting a case involving the simulation of a filament winding process. Filament winding provides an ideal example for this approach, since it is an important manufacturing area that involves the handling of many environmentally sensitive materials as inputs and by-products of manufacturing.

We consider model development within the context of life cycle design. Life cycle design (Keoleian and Menerey, 1993) requires that all design parameters be considered in an integrated fashion from raw material acquisition through final product retirement and disposal. Although this is a goal for which many engineers strive, it is difficult to put into practice because of time and fiscal constraints. Advancements in simulation software have led to the design of user-oriented modular simulation packages which decrease the time needed to build a simulation model and offer opportunities for developing simulation systems tailored to particular needs. By combining modular simulation software techniques and life cycle design techniques with the domain knowledge of a specific manufacturing technology, a simulation system that not only generates traditional production output but also integrates environmental, quality, and cost criteria into the simulation, can be provided.

2 METHODOLOGY

The simulation system being developed can be characterized as being narrower (and more detailed) in application, but broader in scope. First, this simulation system is designed to capture domain knowledge of a specific manufacturing technology (i.e., filament winding) and utilize this knowledge to help design engineers model and compare individual manufacturing options. Therefore, the knowledge on which to base the simulation is deeper than for general-purpose simulations. For example, the knowledge required to develop a traditional simulation for a manufacturing process would typically be limited to the particular process steps, part flow, and all the data on breakdowns, cycle times, labor usage, etc. The knowledge required for a modular, filament winding simulation includes an understanding of all the ways that the manufacturing process could be configured, which possibilities are most often utilized, which are unlikely, and what variables effect the layout. Although an understanding of the data requirements is important, very little data is required to design a modular simulation.

The second difference between this simulation system and traditional simulation model development is the integration of environmental, quality, and cost criteria into the model. Because of this, a thorough understanding of possible material flows, both in and out, is required for each process step and the overall process. Each manufacturing option's material balance will be different; however, the modular simulation must be designed to handle the vast majority of cases. This is one of the most difficult aspects of designing a simulation of this type. Depending on the way the manufacturing process is laid out, scrap and waste products as well as good product will be composed of varying amounts of materials. A thorough understanding of what parameters effect the composition of the input, output, and recycle streams is required so that during the design of the simulation, appropriate variables will be put in place to keep track of each material. A flowchart of the development methodology is shown in Figure 1.

As shown by the figure, there are a number of steps that the analyst must address to build a modular simulation structured to a specific area of application. In step 2, a needs analysis is conducted to determine the systems requirements in terms of the manufacturing process flowchart and the ways in which they can be assembled together, material balances around each process and throughout the overall process, and the decision steps needed to decide what elements and process structure is necessary based upon user inputs. In step 3, the items developed in step 2 are used in the system design. Among the necessary items are sets of questions that the user will need to address for parameter input and to guide the appropriate configuration of the simulation, together with an appropriate database repository for domain knowledge and user input data. From these software to elicit input, update and utilize the database, and execute decisions can be designed. Finally, the simulation modules which will represent discrete processing steps and model changes in material, cost, or energy flows can be designed. These, finally, can provide output statistics generated during the simulation itself and presented to the user in output reports covering material flows, costs, and production throughputs. In steps 4 through 7 these designs are implemented, tested, and validated.

The process depicted in Figure 1 can be considered the preliminary stages for a class of simulation models, and thus it is not surprising that the process is parallel to that required in any simulation study. That is, the stages are a subset of those given in Law and Kelton (1991) for the design of simulation studies. The design of the modular simulation is to build into the modules much of the simulation expertise that would be included in any simulation of this type; including the domain knowledge into the modules means that this information is captured once and can be reused in specific applications. It also means that high fidelity simulations can be produced by users without having to program (or master) all details of the simulation. Modular model designs have been built for specific industries in the past, including MMS (Schroer, et al, 1996) and EMS (Estremadoyro, et al., 1997) for the apparel and electronics industries, but SimBuilder represents a more detailed implementation than these previous examples.

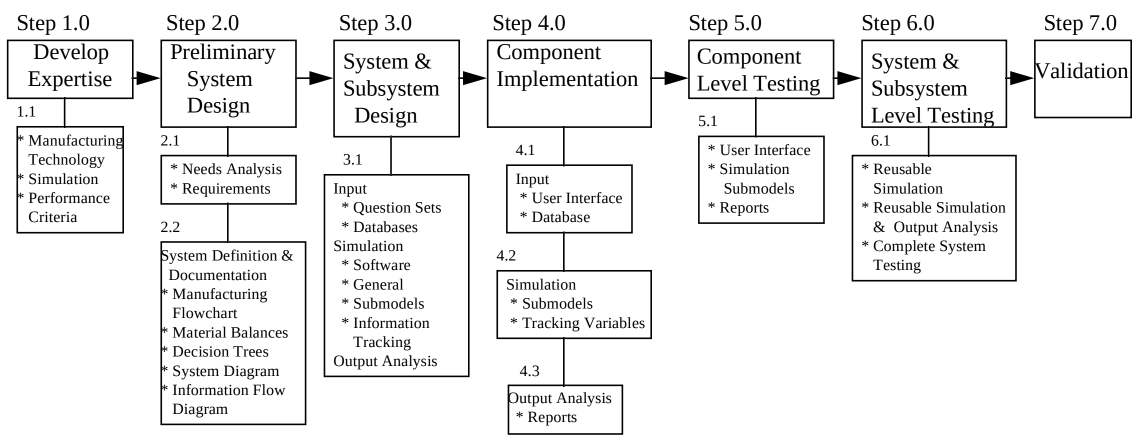

Figure 1: Flow Diagram of Methodology for Designing and Developing a Modular Multi-Criteria Discrete Event Simulation

3 EXAMPLE: FILAMENT WINDING

The filament winding process consists of up to six main process steps, which include mandrel preparation, filament winding, curing, mandrel removal, finishing, and quality inspection (Groover, 1996). The first step is mandrel preparation where either a one use or reusable mandrel is placed on a reusable arbor and prepared. During mandrel preparation mold release can be applied to the mandrel, the mandrel can be cleaned, a liner can be applied to the mandrel, and parts can be attached to the mandrel. During the second step, filament winding, composite materials are wound around a prepared mandrel. Wet or prepreg composite materials can be used during filament winding. The third stage, curing, is done either at room temperature, in an oven, or in an autoclave. If an autoclave is used, parts must be enclosed in a bag for protection. Processing can be either batch or continuous. Curing can also occur in two stages, pre and post cure.

Once curing is completed, mandrels and arbors are removed from the cured part during the fourth stage. The arbors and reusable mandrels are sent back to mandrel preparation to be used again. Solvents may be necessary to aid in the removal of some "one use" mandrels. The finishing process includes three different types of operations: machining, cutting, and assembly, any combination of which is considered finishing. Quality inspection, the last step in the process, allows parts to be inspected individually or in a batch. All poor quality parts (scrap) are assumed to be discarded as soon as they are produced. This implies that discarded parts are visually inspected during processing. Poor quality parts (scrap) which can not be visually inspected must be carried through to the quality inspection process (Board of Environmental Studies and Toxicology, 1990; EPA, 1991).

The flowchart (Figure 2) below was one of the tools developed and used extensively throughout the design of the filament winding simulation system to summarize the options and parameters to be considered in filament winding processing. Not all parameters were needed in all applications, so inputs would be required from the user to specify which would be needed in a particular application. For instance, mandrels can be reusable or one-use, the latter being of various types. As noted earlier, question sets were designed to elicit and act upon information supplied by the user. As an instance, bag materials would be required when autoclave curing was selected, and otherwise not.

4 SYSTEM DESIGN

Figure 3 shows that the filament winding SimBuilder simulation system is composed of three subsystems, the input system, the simulation, and the output system. The purpose of the input system is to ensure that all required information is obtained from the user and available for use within the system. This includes developing the format and questions for the user interface and the databases used to store user input data. The second subsystem is the simulation. The simulation subsystem uses the information

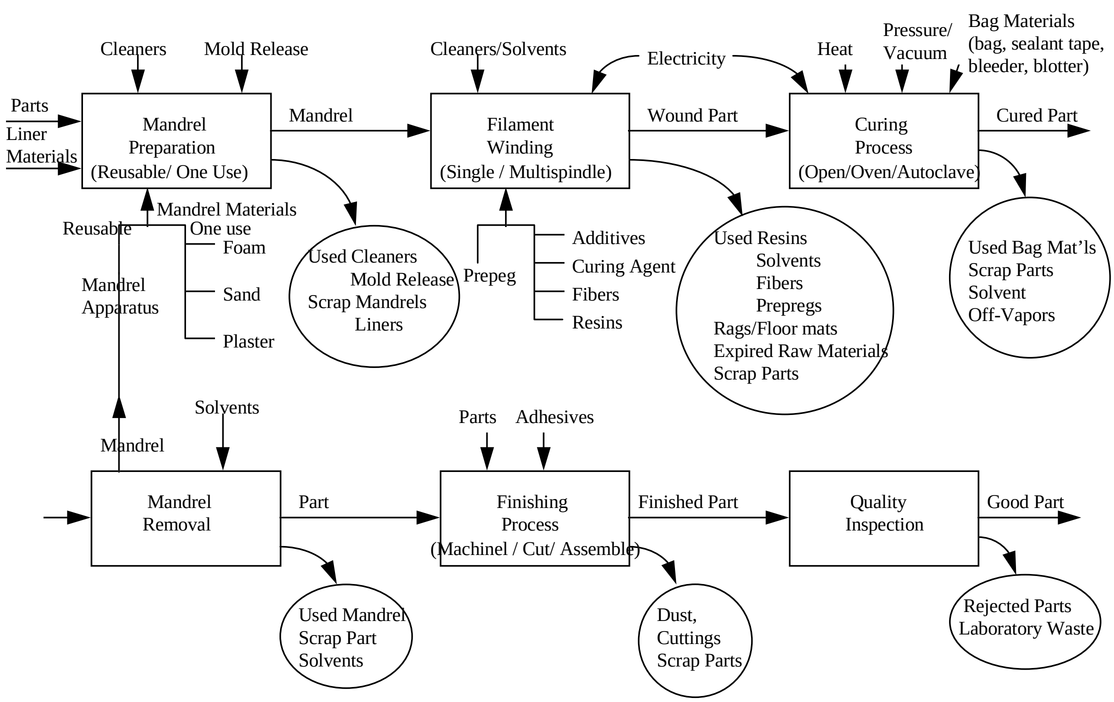

Figure 2: Filament Winding Flowchart

obtained from the user to develop and run the simulation model and to generate information needed for the output subsystem. This includes developing submodels for all the process steps and creating system variables, which will track the required information. For this application, there were a total of six main process steps, given above, and a total of twelve distinct submodels. Mandrel preparation, filament winding, and mandrel removal required only one submodel each. The variety of processing methods available for curing, finishing, and quality inspection dictated the use of four, three, and two submodels, respectively. The output subsystem utilizes information from the user and the simulation to generate material, environmental, quality, cost, production, and energy reports.

4.1 Input Subsystem

An important aspect of the simulation system is the input subsystem, which consists of both the user interface and the database. The user interface questions were developed for this application based on the flowchart (Figure 2) which details the overall filament winding process, process flow charts and material balances for each individual process step, the simulation software, and the needs and requirements of the users. The questions fell into nine general categories including materials, labor, breakdowns, scheduled maintenance, set-up procedures, cycle time, energy usage, configuration, and quality. Not all categories were used for each submodel's question set because of differences in the main process elements (i.e. an oven vs. a conveyor) and the absence of material and energy usage during certain process steps.

Certain databases were developed to store information, which were not directly used to populate the simulation but were needed for the output analysis. The material database, the most important, consisted of 1) a general section which contained general information about the materials being used including the name, cost, and Material Safety Data Sheet (MSDS) environmental information, and 2) the option specific section which included information required for each simulation experiment. This included, for example, the amount of material used for the original part and the percentage of the part discarded during certain operations. All of the information required for the material database was captured from the interface questions developed for the submodels.

4.2 Simulation Subsystem

WITNESS (1997) was the software selected for this research effort based on the follow criteria: cost/availability, ease of use, reusable design capability, flexibility, and data transfer and access. Utilizing the capabilities of WITNESS the materials/parts and process steps were evaluated individually with regards to how they should be modeled. It was determined that most of the material usage's would be calculated in the output reports by multiplying variables already available in WITNESS by some constant usage rate entered by the user. Solvents used for cleaning during the filament winding operation were tracked through the use of variables, which were designed, into the simulation model. The only simulated "parts" were the mandrel, the reusable bags, and the part itself in its various stages of production. This decision simplified the simulation and reduced the number of submodels needed for each processing step.

Twelve different submodels were developed which included simulated elements such as 1) buffers, 2) a main processing element, 3) variables which were needed for

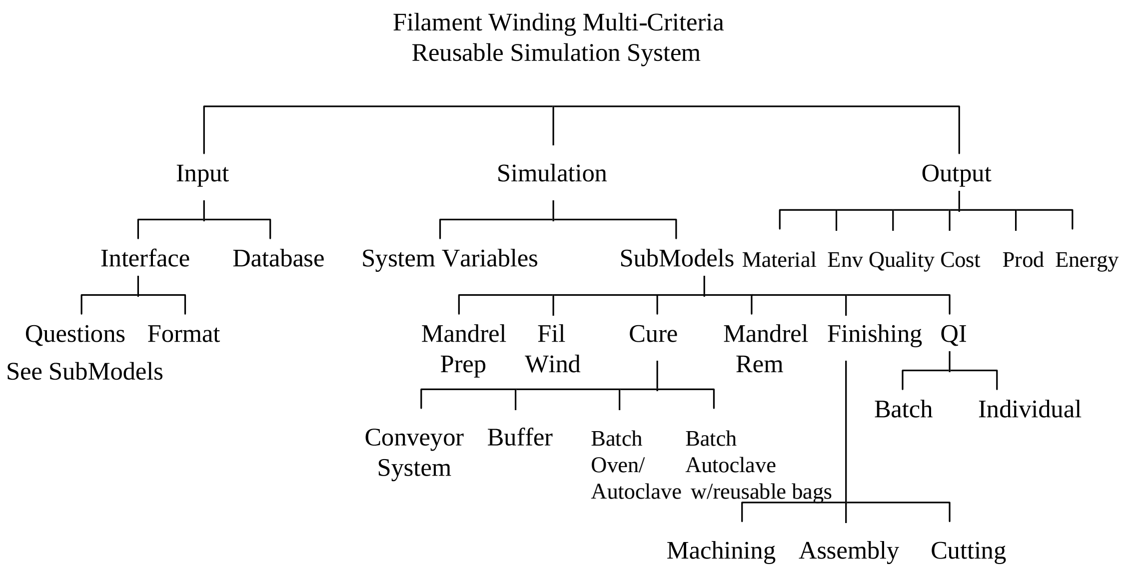

Figure 3: System Diagram for Filament Winding Simulation System

material balance calculations, 4) quality distributions to determine the percent sent to scrap at each processing operation, and 5) labor. The submodels that were developed can be found on the system diagram in Figure 2.

Because of the complexity of the material balance calculations the allowable placement of the submodels within the simulation had to be determined. The user was allowed two main configurations for filament winding manufacturing. Each of the main configurations had many minor variations, which gave the user needed flexibility. The first configuration begins with the mandrel preparation and filament winding which are both required steps. The part then goes to a curing process that can be any of four submodels. The mandrel is then removed. From the simulation's viewpoint, mandrel removal is the last required processing step. The part can then be sent to curing, finishing, quality inspection, or shipping. If a post cure is required the part is sent to another curing process. After curing it can be sent to finishing, quality inspection, or shipping. Any or all of the submodels can be used in any order for both the finishing and quality inspection processing steps. All curing must be completed before finishing is started, and all finishing must be completed before quality inspection is performed. The inherent difficulties in tracking all materials in and out of a submodel dictates that, at this time, a submodel can only be used once in a simulation.

The second configuration allows the part to be post-cured and machined (one of the three finishing operations) before mandrel removal is performed. Mandrel removal is still the last required operation. From mandrel removal the part proceeds to the other two finishing operations, quality inspection, or shipping just as in the first configuration.

4.3 Output Subsystem

Six basic output reports were developed to effectively communicate information to the user. The reports developed were: 1) the material report which includes the amount of each material that enters the system, exits the system in each output stream (good parts, mandrel prep scrap, etc.) and remains in the system as work in process, 2) the process report (from WITNESS) which includes traditional simulation output, 3) the quality report which includes the amount and cost of all scrapped materials by processing station and type of material, 4) the environmental report which includes the amount and cost of all materials discarded as waste, 5) the energy report which includes the amount and cost of the energy used to produce the parts, and 6) the cost report which includes material, energy, and labor costs for producing the parts.

5 CONCLUSION

In this paper we develop a methodology for developing applications specific, environmentally focused manufacturing simulations and illustrate that methodology using filament winding manufacturing. Compared to generic manufacturing simulation, materials and waste streams are explicitly represented as well as discrete parts flows. To limit the modeling burden upon manufacturing analysts, these considerations are designed into the simulation system by an interactive front end that selects the necessary modeling elements based upon analyst input. The amount of specialized knowledge required limits the area of application, though the simulation model being built is more complete in terms of its representation of the manufacturing process and its costs. These costs include scrap and waste, as well as the specialized problem of wastage due to aging, collection and disposal of hazardous materials, and production items such as bags, mandrels, and the like. For industries where these costs are not incidental, a complete accounting will make an accurate cost estimate possible.

The methodology is illustrated for filament winding manufacturing, an important area of manufacturing for which environmental costs are not incidental due to the use of resins, prepreg, and solvents during the process. The filament winding manufacturing technology was used to illustrate the system architecture, which included three major subsystems. Although modular simulation software has been available for a number of years, embedding manufacturing domain knowledge into an expert system-like front end and integrating environmental, quality, and cost criteria into the simulation makes SimBuilder unique.

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