Modeling and Simulation Analysis Types for Sustainable Manufacturing

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ABSTRACT
Sustainable manufacturing could be promoted by the effective use of Modeling and Simulation (M&S) applications. These applications can evaluate manufacturing operations in light of increasing legislation and awareness for environmental protection. They can help determine the operational policy and strategy, and evaluate day-to-day manufacturing decisions to comply with regulations and to improve a company's image. However, in order to accomplish these objectives, existing and future simulation applications need to be enhanced to include sustainability constructs. This paper describes a classification of M&S application areas along functionality and data requirements axes that are necessary to achieve sustainable manufacturing objectives. The classification can in turn be used to perform requirements analyses for those applications and develop data repositories necessary to build and execute the simulation models.

Categories and Subject Descriptors
I.6.1 [Simulation and Modeling]: Simulation Theory – *model classification, systems theory.*

General Terms
Management, Measurement, Documentation, Performance, Design, Human Factors, Standardization, Theory.

Keywords
Sustainable manufacturing, metrics, sustainability data, simulation analysis requirements

1. INTRODUCTION
Manufacturing systems use raw materials and auxiliaries such as water and air, and transform them into finished products. The transformation process requires inputs of energy. Solid and liquid wastes and gaseous pollution are often produced as byproducts of the manufacturing process. Figure 1 shows the basic inputs and outputs of a manufacturing system. Therefore, production systems and production activities can have both positive and negative impacts on the natural environment, natural resources, economy, and the surrounding communities. The negative effect may imply that soil is contaminated, and natural resources, water sources, energy sources, and pristine land mass depleted at such a rate that manufacturing activities cannot be sustained in the long-term without exceeding the natural limits. With this new awareness to minimize the impact of economic activities on the environment and natural resources, the term "sustainable manufacturing" has been coined**.**

The Sustainable Manufacturing Hub (Sustainable Manufacturing Hub 2009) defines sustainable manufacturing as *"creating a product in a way that considers the entire product's life cycle and its full impact surrounding the use and reuse of raw materials and auxiliary materials, impact on the environment and impact on the surrounding community the goal is to be able to manufacture in a way which is so sustainable that it is able to continue into the future."* This definition implies the importance of analyzing a product's impact by considering its entire life from raw material acquisition to its disposal and, if possible, recovery and reuse of its components or materials into new products.

This paper gives an overview of the types of simulation models that can be developed for sustainable manufacturing along the axes of product life cycle and data requirements. It contrasts traditional simulation model objectives and sustainable objectives, and highlights the types and role of data in these models.

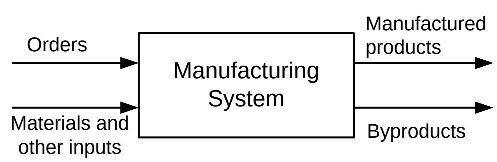

Figure 1. Basic inputs and outputs of a manufacturing system

What is simulation? Simulation can be defined as "*the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments to give us a better understanding of the behavior of that system for a given set of conditions"* (Kelton et al. 2004). Modeling and simulation (M&S) methods have a high potential to contribute to sustainable manufacturing. Therefore, it is necessary to capture and formalize descriptions of the product design, manufacturing, use and disposal processes, and their interactions. Because of the complexity of the problems, M&S

will play a large part in understanding (Rachuri et al. 2009). As such, M&S applications can play an important role in decision making either before or during each stage of a product's or production system's life cycle. Such stages include site selection, product design, production system design, machine and process selection, material selection, product useful life, product replacement, and product disassembly and reuse/recycle. A simulation model can be developed for targeted stage in a product's life or one model could be constructed to simulate the entire product lifecycle. An example of this is the Arena model developed to investigate lifecycle cost reduction in domestic appliances for manufacturers under the Waste Electrical and Electronic Equipment (WEEE) regulation for product sale, product use, repair, and disposal (Xie et al. 2006).

By describing what to simulate, the classification of objectives would support to perform requirements analyses of M&S tools for enhancement and development of new applications for sustainable manufacturing. The rest of the paper is organized as follows: the next section reviews literature related to simulation of sustainable manufacturing and classification strategy. Section 3 describes the classification issues along the dimension of functional requirements for the simulation model. Section 4 presents a description of the data requirements for executing the simulation models. Section 5 describes an example of a simulation model that can be developed to include sustainability concepts in the functions, and its data requirements. Section 6 concludes the paper.

2. RELATED WORK AND SIMULATION CONTEXTS

2.1 Assessing Sustainable Manufacturing

A region or country can be assessed whether or not it is on a trajectory to sustainable development by measures such as genuine savings; ecological measures such as human appropriation of net primary production, ecological footprints and environmental space; and socio-political measures such as index of sustainable economic welfare (ISEW), and quality of life indicators (Moffatt et al. 2001). In a standardized Life Cycle Assessment (LCA) the goals are first defined to eliminate the case where some indicators can be seem as conflicting. Lifecycle simulation has also been proposed to evaluate the effectiveness of different lifecycle phases, i.e., remanufacture, reuse, recycle, maintenance, and final dumping (Takata et al. 2003). By this method the given parameters, indicators, performance metrics, and indexes are defined, tracked and evaluated against set benchmark values.

2.2 Modeling and Simulation Issues

M&S tools have been used for sustainable manufacturing for specific cases. For example; collecting and recycling policies of used products under the Extended Producer Responsibility (EPR) system (Kamazawa and Kobayashi 2003); evaluating process design for optimizing material and water consumption (Turon et al. 2005); selecting processes to be outsourced, new suppliers, and new manufacturing styles by using life cycle simulation by original equipment manufacturers (Komoto et al. 2003); evaluating alternative operating processes regarding CO2 emission, energy use, resource use, and waste in a smelter plant (Khoo et al. 2001); determining manufacturing for environmental waste and indirect costs associated with disposal and containment (Russell et al. 1998); and reducing and streamlining material, energy used, and cost of energy (Sakai et al. 2003). Environmental and ergonomic issues have been analyzed using simulation (Heilala et al. 2008) and an integrated framework for analyzing both economic and ecological objectives in manufacturing has been developed (Herrmann et al. 2007).

The review described shows that simulation of manufacturing systems for sustainability is scanty and scattered. There is also a lack of concerted effort to structure requirements for modeling, simulation and analysis of sustainable manufacturing.

2.3 Decisions at Different Abstraction Levels

Different decisions are made at different levels of hierarchy. The interaction between the decision making systems can complicate the process of achieving economic, social, and environmental objectives. Each level may require a different simulation study type due to different data and analysis objectives. For example, the evaluation of impact of decisions on overall business performance is a long term strategic decision as opposed to determining a daily production schedule, which is a short term operational decision.

Industrial Policy

M&S is important for decision making at the industrial level for long term or strategic planning because of the increasing complexity of systems, processes, and data. At a macro level, sustainable manufacturing policy can be determined by the use of system dynamics modeling. System dynamics facilitates decision support for policy making by helping to determine long term effects of industrial activities on natural resources, energy, and the environment. It can also evaluate the impact on the economic viability of the industry. To benefit from these models, the analyst needs to first determine the indicators of manufacturing sustainability. Measures such as genuine financial benefits, ecological measures such as pollution, ecological footprints, and environmental space need to first, be defined. The inputs to this model would be factors such as population, investment, interest rates, imports, regulatory policies, incentive, and taxes.

Factory and workstation level

M&S for sustainable manufacturing at workstation and machine level can be done in different ways, depending on the objective. Workstation simulation can determine setup to improve waste handling and disposal. It can also help determine human-machine interaction to reduce energy use and toxic waste. Virtual reality can also be used to determine the ergonomic and kinematics movement of resources during operation. In can also analyze issues such as worker safety, and posture noise level and measures.

Process

M&S of machining operations, called virtual numerical control, is used to validate numerical control (NC) program, to ensure that the program would produce the part and to prevent possible machine crashes and damage. Thus, a module can be attached to the virtual machine model to track the energy consumed, quantity of coolant used, wastes generated, quality, surface finish, and gaseous pollution for an operation.

M&S can guide to select a particular model of NC machine tool for a job given the stock and required product. Different machine tools could have different specific energy consumption for machining given engineering materials. As M&S determines whether a given NC program can produce the part it can also determine sustainability indicators. With this approach, production scheduling will not only produce a schedule which can best utilize resources and meet customer requirements but also minimize the environmental impact of a given work order.

2.4 Classification Strategy

The classification identifies the nature of the simulation, i.e., the major issues and elements within sustainable manufacturing that are to be modeled. These issues form a basis for identifying the functionalities required within the simulation applications. The need for M&S is often due to, for example, the introduction of a new manufacturing plant in a community, evaluation of effect of compliance with a newly introduced environmental regulation, or modification of existing manufacturing process for a particular purpose. We identify two dimensions along which to perform the requirements analysis and classification. The first is the stage in the product lifecycle. The other dimension is the data categories.

3. REQUIREMENTS ANALYSIS – FUNCTIONAL

This section describes the functional requirements of a simulation model for traditional and sustainable situations. These two situations or views form the structure of the work to be described in this section.

3.1 Product Lifecycle

The stages in a production lifecycle start with product design and end with disassemble, reuse, and recycle. At each stage, different simulation models need to be constructed. It is the requirements and goals of the simulation model at each stage that will form the basis for problem classification. The Figure 2 shows the hierarchical display of the stages.

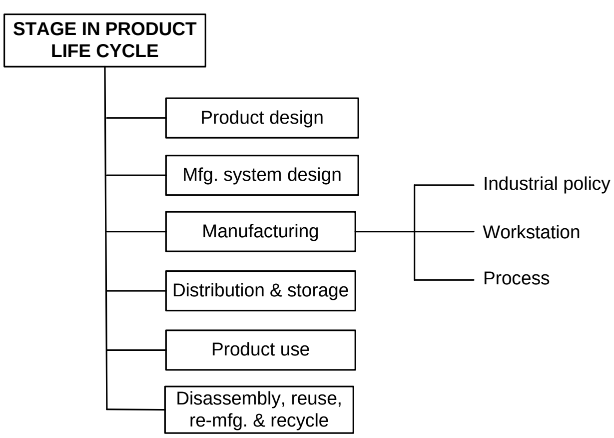

Figure 2. Framework for classification of sustainable manufacturing M&S problem types

3.2 Functional Categories

3.2.1 Product Design

Product design defines the determination and specification of components of a product so that they all function as the requirements specify. The design phase is important because it is estimated that 70 to 80 percent of the product cost is determined by decisions made during the design stage (Savari et al. 2008). It is beneficial to introduce Lifecycle Engineering early in the design stage and assess both ecological and economic impacts of a product design. There are many areas in the design process where M&S can play a major role. They include performance analysis, process planning and manufacturing requirements, and economic and safety objectives.

Performance

Traditional – Eliminate the need to build physical prototypes as a means of determining behavioral characteristics and manufacturability before a product is eventually built. As such, product simulation is carried out to understand the problem that the design intends to solve, and a synthesis phase in which the solutions are generated. The different solutions are evaluated using M&S. Novel approaches such as Applied Signposting Model (Wynn et al. 2006) used to simulate the effect of design on various options for manufacturing in a concurrent engineering environment.

Sustainable – Test alternative designs, materials, and component parts with a view to analyzing energy consumption during production and use, product durability, and pollution. It can also be useful in issues such as investigation of product function when using alternative operating conditions.

Process planning and manufacturing requirements

Traditional – Virtual reality simulation of assembly processes where, through the concept of virtual manufacturing, the parts manufacturing and assembly of a product can all be done in a 3-D simulated environment. M&S is also useful to evaluate different process plans for product flow time, facilities utilization, alternative work flows, resource utilization, waiting times, and load balancing.

Sustainable – Model the process according to clean manufacturing processes, equipment, and the use of alternative materials.

Economic

Traditional – Assessment of costs involved in materials purchase, parts production, labor, and equipment.

Sustainable – Analysis of costs of sustainable inputs and toxicity of materials, cost of non-compliance, material reuse, tradeoff between sustainable process costs, and maintenance and disposal costs under the extended user responsibility.

Safety

Traditional – Evaluation of worker capacity and physical burden and strain to carry out the task for efficiency of operation, allowance for resting, and production rate while minimizing or eliminating injury to person. Reduction of claims and expense from worker related health problems and/or loss of body part.

Sustainable – Place greater emphasis on safety, including exposure to hazards, injury prevention mechanisms, and elimination of potential harm from infection. Emphasize long-term health by elimination of carcinogens, task diversification, and employee morale.

3.2.2 Manufacturing System Design

Manufacturing system design involves equipment specification, determination of labor requirements, and layout. This process normally follows product design so that the required facilities, equipment, machinery, staffing, and control systems can be put in place to manufacture the product. In case of jobbing shops, a production system may already be in place and equipped with general purpose machine tools with given capabilities. New product designs or orders are accepted on the basis of equipment capability and capacity. However, it is also possible that a new product design would need modifications on existing equipment and facility layout. But with concurrent engineering the design of the product and manufacturing system design would take place simultaneously.

Regardless of the situation, M&S can be used to select a manufacturing process and in turn determine the requirements. Effective design of a manufacturing system using M&S contributes to efficiency and sustainability of its operations.

Manufacturing process selection

Traditional – Evaluate and select manufacturing processes that are cost effective and efficient in operation, matching machine capacity, labor skills, and operator comfort.

Sustainable – Evaluate and select process for minimal environmental impact such as evaluation and selection between casting and sintering in the making of some classes of products.

Manufacturing facilities selection

Traditional – Investigate equipment capability and identify problem areas, quantify or optimize system performance under different loading conditions and investigate queue sizes, resource utilizations, existence and identification of bottlenecks, and staffing levels. Determine effect of facilities on throughput.

Sustainable – Consider additional sustainability issues to equipment such as pollution, greenhouse gas emissions, maintenance requirements, equipment life while carrying out the selection process.

Manufacturing facilities layout

Traditional – Evaluate effect of different layout configurations on system performance, floor space requirements and materials handling costs, buffer storage needs and throughput, effect of materials handling, storage areas, scheduling, and determination of work routing.

Sustainable – Evaluate effect of layout on factors such as energy usage, machine idle times, operational and maintenance accessibility, and housekeeping.

Materials handling

Traditional – Determine material handling capacity, materials holding storage, sufficient space for movement, level of automation, visualize proposed system, integration of materials handling with other manufacturing systems and testing of alternative handling policies.

Sustainable – Minimize energy costs in handling, reduction of handling, deployment of reusable containers and containers, and the use of sustainable materials handling methods.

3.2.3 Manufacturing

One of the largest application areas for M&S is that of manufacturing systems, with the first use dating back to at least the early 1960's (Law and McComas 1997). Hence, manufacturing is perhaps the largest application stage in product realization because of the large potential for performance improvement and the need to avoid costly mistakes. Current M&S applications enable analysts to model and validate manufacturing processes, work flow, schedules; introduce new products and processes; determine material, labor, equipment, tooling, inventory, material handling, and maintenance requirements; and plan for equipment breakdowns and repairs. However, the current commercial off-the-shelf simulation tools most often do not address sustainability.

Planning and control

Traditional – Reduce costs, minimize production lead times, evaluate schedules, and improve product quality. Others are to identify bottlenecks, determine inventory policies, throughput, and capacity (equipment and personnel) utilization. Also, evaluate effect of inventory policy, location, size, deliveries, and inventory tracking mechanisms on system performance.

Sustainable – Determine material, energy, and waste flows in manufacturing and consideration of issues such as energy or water used per unit of final product.

Quality improvement

Traditional – Determining the number of inspection stations, their placement and impact on throughput and outgoing quality. It can also be used in investigating the effect of process parameters on defect formation in the product.

Sustainability – Investigate the shift to sustainable manufacturing processes and products and the effect that the shift can have on product quality.

Maintenance management

Traditional – Determine optimal preventive maintenance policy, sizing of repair crew and tools for dealing with breakdowns, improving system life, improving production and quality, and safety. M&S can support decision making to determine operating policy, performance management, dynamic maintenance system, maintenance cost control, and system downtime.

Sustainable – Investigate use of more environmentally friendly parts, lubricants, and procedures. Schedule maintenance to collect used parts in bins of same material composition for easy recycling or rework. M&S can be applied to evaluate and decide maintenance procedures and policy for longer product service and optimal policy for product (especially equipment) replacement.

3.2.4 Distribution and Storage

Virtually all products from the manufacturer pass through a distribution system that involves storage and handling until it reaches the final consumer. Control of the distribution system is concerned with measuring the cost, service level, and flexibility or a tradeoff while considering different strategies and structural conditions. By selecting a criteria or measure of performance, an analyst can determine an operating policy or strategy.

Distribution and warehousing strategy

Traditional – Meeting delivery requirements, minimization of costs, and customer satisfaction. For a new supply chain that means location of distribution points and fleet capacity, and determination of optimal inventory levels.

Sustainable – Minimization of costs while considering environmentally friendly transportation and storage alternatives.

3.2.5 Product use

M&S of a completed unit of product use could include different ranges of operating conditions such as loading and environments, to ensure that it would perform as designed. This helps to increase product confidence in manufacturers and users by using virtual testing to cover a range of product usage situations.

Product maintenance

Traditional – Evaluate component and product reliability, availability and maintenance. Such an analysis can be used to determine maintenance crew and policy and what the benefits are of reduction of breakdowns.

Sustainable –Develop more conscientious maintenance programs for support equipment. This includes heating, ventilation, and air conditioning systems in work areas so as to reduce outputs of pollutants, energy use, and maintenance costs.

3.2.6 Disassembly, Reuse, Remanufacturing, and Recycle

In recent years, interest has increased in recovering and reusing materials from products after the end of their lives. Products are now designed for easy recovery of materials for reuse. The term “end of life product” has been changed to “end of use product.” The main reasons include increasing cost of materials, rising cost of disposing used products, toxic substances being dumped into the environment, and government legislation.

Traditional – Evaluate product design for least cost, shortest time, etc. for disassembly and optimal communication of disassembly information and optimal sequence of disassembly processes.

Sustainable – Determine: i) recycling and reuse policy for local, state or federal government, ii) technologies for recycling, iii) the cost of recycling, iv) the end of life recycling value in a product, v) material and recovery reclamation strategy, and vi) whether to reuse, remanufacture or recycle an end of use product.

4. REQUIREMENTS ANALYSIS – DATA

M&S for sustainable manufacturing requires data for quantitative information to execute the models and obtain results to aid decision making. This section overviews this data.

4.1 Role of Data

The simulation models for each stage of product life cycle and abstraction level would typically require different types of data. Simulation execution data is input for a particular model or run. Stored data or reference data should be available for access by any simulation model and can be stored in plain text format or in remote databases. It could also be stored in relational databases. Figure 3 shows the relationship between data input, the simulation model, and output. This data can be categorized in the domains: environmental, social, and economic.

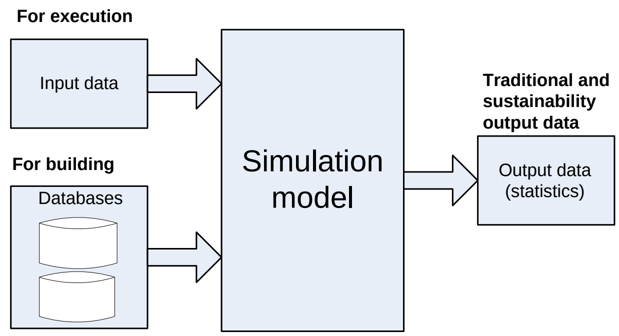

Figure 3. Process flow for sustainable manufacturing modeling and simulation

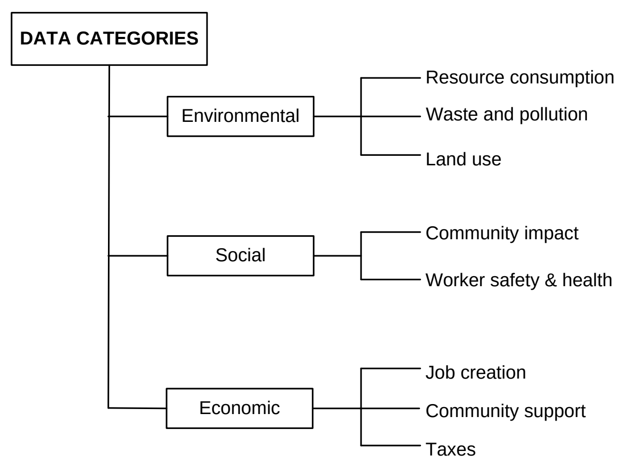

Figure 4. Classification of M&S data requirements for sustainable manufacturing

4.2 Data Categories

4.2.1 Environmental

The categories of data relevant to environmental impact are resource consumption, waste and pollution, and land use.

Resource consumption

This refers to natural resources available and those required in making the product. Such resources include raw materials, energy, air quality, and water. Different manufacturing systems consume different resources. The excessive use of local natural resources can affect both plant and animal life in the community.

Waste and pollution

Quantity and type of waste and emission produced throughout a product's life cycle. This category includes all solid, liquid and gaseous byproducts with a description of their content and lethal potential. Pollution includes also that produced by energy producers and transporters. Noise is also a form of pollution.

Land

This refers to the land available and land use per unit of product and for disposal of waste.

4.2.2 Social

This is the data input to evaluate the social impact of the investment on the population. The type of modeling relevant for this category is the continuous high-level simulation for policy setting. It is perhaps one of the most difficult to quantify and evaluate. The key elements in the social domain are:

- General population and health status
- Potential manufacturing workforce
- Skilled people
- Housing
- Community amenities
- Other manufacturers as social institutions
- Supporting infrastructure and institutions
- Social laws and regulations

4.2.3 Economic

Economic data is relevant for all levels of abstraction from the decision to set up a manufacturing plant to the payment of manufacturing bills. The income largely comes from sales and other benefits or services. The cost for each stage in product life cycle, i.e., material, labor, equipment (plant), energy, water, transportation, fines, and taxes is set against price tag and sales. Other economic data categories include:

- Financial markets
- Financial regulations
- Financial institutions
- Shareholders
- Individual wealth in the community
- Disposable income
- Manufacturing wages
- Manufacturers as financial entities
- Manufacturing throughput
- Manufacturing profits
- Other manufacturing investments

5. EXAMPLE OF SIMULATION MODEL

5.1 Machining Manufacturing Modeling

Machining falls into the categorization of manufacturing where the concern is production planning and control, quality, and maintenance. The objectives include: minimize waste, energy use and meet production requirements.

Machining uses energy, cutting fluids and lubricants that have to eventually be disposed of as waste. The chips formed during the process are often mixed with these fluids, and have to be cleaned before recycle. Cutting tools, made of hard materials, have a large life cycle environmental impact. Overall, machining is a "dirty" process with a negative impact on the environment. Therefore, modeling and simulation of the process using virtual numerical control for manufacturing sustainable products could aid decision making to reduce the environmental impact.

After a virtual model of the machine is constructed, the next step is to input the models of the part blank and the cutting tools to produce the virtual product. The part stock size and geometry plays an important role for deciding how much waste will be generated, energy consumed, and production time. The numerical control (NC) program is the basic input to the virtual machine, required, and is validated using the model. An optimized NC program may mean shorter production time thereby reducing energy consumption, tool usage, coolant and lubricant, and total emission. Different NC programs provide different scenarios for calculation of the environmental impact. Other controlled variables such as speed of cut and depth of cut influence cutting conditions and substantiality output. In addition, different NC programs for the same design part can be used to evaluate the difference in environmental impact. This analysis has functional and data requirements.

5.2 Functional Requirements

Modeling NC would need functionality to represent and visualize the machine tool, and input the workpiece, cutting tool, and NC program in addition to sustainability constructs. These are the machine tool builder, machine tool controller, machining process, energy use, coolant, and lubricant. The outputs are models of product, solid waste, liquid, waste, gaseous waste and other sustainability reports. It should also be able to model relationships between different sustainability indicators so that they can be evaluated with a common unit. There should also be functionality to vary different controllable inputs in the model. Other requirements are connections to databases and any optimization function and display of sustainability reports.

5.3 Data Requirements

Validation data

This process requires data. Some of this data is substituted into the simulation model by that particular run. Such data includes the NC program, work piecework model, and cutting tool data. The other is stored reference data.

Reference data

This is any data other than what can be provided by the model for the determination of the environmental impact. It includes machine specification data, lifecycle assessment (LCA) data, cutting speed data, feed rate, specific energy tables, tool tables, spindle power specification, and other real world data.

Real world data is collected from machine systems on the shop floor. The data could be collected directly from devices or come from a database or other information system. For example, the output that includes sustainable data from a real machine may be extracted by the following systems:

- **MTConnect**

This is a data exchange standard that allows for disparate entities in a manufacturing system along with their associated devices to share data in a common format. This middleware standard can facilitate direct extraction of data from Computer Numerical Controlled (CNC) machines during operation to other systems for further processing using the eXtensible Markup Language (XML) standard (Vijayaraghavan et al. 2008).

- **The Object Linking and Embedding for Process Control (OPC)**

OPC is a technique for monitoring manufacturing systems and their status (OPC Foundation 2010). The OPC standards specify the communication of industrial process data, alarms and events, historical data and batch process data between sensors, instruments, controllers, software systems, and notification devices.

6. CONCLUSIONS AND FUTURE WORK

This paper has presented an overview of the class of sustainable manufacturing simulation problem types and data. Different levels within each category and objectives of modeling have been discussed for both traditional and sustainability approaches. It has been found that M&S applications for sustainable manufacturing are relatively few and are often geared to the solution of a given problem using existing simulation models in their current form or a combination of approaches. Enhancement of M&S for sustainable manufacturing will require new metrics and standards and standards interfaces to be developed. It will also need a depository of data to execute simulation models and compare output against the best in class performance. To support sustainability, modeling tools will need to provide additional functional capabilities as well as validated methods and models that will help the analyst develop technically correct simulations. This paper has described the requirements. This description can then be used to perform requirements analysis for the applications that could form the basis for enhancement of or development of the required simulations systems and the model structures.

What remains to be done includes the description of characteristics of each type of simulation model and objectives, and searches into the sources of data. It would also link the data to the simulation model type.

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