MODELING AND SIMULATION FOR SUSTAINABLE MANUFACTURING

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ABSTRACT
With increasing frequency the news media reports that the planet is warming, pollutants are contaminating the environment, energy costs are rising, and precious natural resources are dwindling. These reports are sounding an alarm that we need to change the way we manufacture products so as to minimize the negative impact of industrial operations on the environment, the workforce, and the surrounding communities. Simulation technology has been a significant tool for improving manufacturing operations in the past; but its focus has been on lowering costs, improving productivity and quality, and reducing product time to market. In the future, it could similarly help us to achieve green, environmentally friendly, or as it is commonly called today, sustainable manufacturing. Changes will need to occur if simulation is to be applied successfully to sustainability. Manufacturers will need to focus on issues that they have not been concerned with in the past. Since there has not been a demand for simulation technology with sustainability features, software vendors and analysts have not typically addressed these issues. This paper presents a vision for modeling and simulation that supports sustainable manufacturing that is based on changes to simulation case studies, metrics, software tools, interface standards, and data sets.

KEY WORDS
Manufacturing, modeling, simulation, sustainability, metrics

1. Introduction

In this section the negative impact of manufacturing activities on the environment is outlined. Of great importance, pollution and global warming are particularly singled out. A more environmentally friendly approach to manufacturing has been termed "sustainable manufacturing." It also describes how, in the past, simulation has been effectively used as a tool for improving manufacturing productivity and could be used to achieve sustainability in the future. The benefits of simulation technology are briefly described.

1.1 The Negative Impact of Manufacturing

It should be obvious to a casual observer that manufacturing has often had a significant negative impact on the environment. One only needs to visit a city with a steel plant, a chemical refinery, or other heavy manufacturing industry to see, and often smell, some of the negative effects of manufacturing on the environment. The effects that have been attributed to manufacturing include global warming and green house gas emission; contamination of the air, water, and soil; consumption of significant non-renewable resources; and excessive generation of waste products.

According to a National Academies of Science (NAS) report "there is a growing body of evidence that the earth's atmosphere is warming." The temperature of the earth's surface has gone up by about 0.7 º C during the twentieth century [1], with the highest rate of increase recorded during the last thirty years, corresponding with the increase in industrial activity. The earth's climate has always been changing but the current change, especially global warming, is attributed to human activities.

Since the beginning of the industrial revolution about 250 years ago, the concentration of greenhouse gases responsible for global warming has increased greatly from 280 microliter/L to 375 microliter/L today [2]. The rate of increase of these gases has overwhelmed the natural processes that remove them from the atmosphere. The current annual world greenhouse gas emission from human activities is about 25 billion tons, about a quarter of this from the United States alone [3].

The main greenhouse gases are water vapor, carbon dioxide, nitrous oxide, methane and chlorofluorocarbons (CFC). Human activities have little impact on levels of water vapor. Therefore, it is of no concern. Methane originates from natural gas leaks, decomposition of living tissue and dairy farming. Oxide greenhouse gases form during the burning of fossil fuels, which have been the main engine driving industrial growth. However, by far the most emitted gas, a direct result of manufacturing activities, is carbon dioxide. These greenhouse gases are currently at their highest levels in the last 400, 000 years [1]. Past records show that global temperatures have been rising and falling in the same pattern as the concentration of carbon dioxide in the atmosphere. Extreme weather events of the last several years have raised a question as to whether this is caused by global warming [1]. It is also expected that if this phenomenon persists Arctic and Antarctic ice would melt, with catastrophic consequences, especially for coastal settlements. Aside from this concern for global warming, the increase in demand and price for petroleum and other fossil fuels, coupled with reduction in available reserves, have resulted in greater efforts to reduce energy consumption.

Besides global warming and climate change, manufacturing activities inevitably generate large amounts of industrial waste. American industrial facilities generate and dispose of approximately 7.6 billion tons of industrial solid waste each year [4]. This waste consists of leftover materials used in products or byproducts of production processes. Increasing quantities of these products requires space, and they should be treated before disposal to minimize the environmental impact. Hazardous waste includes heavy metals, inks, solvents, acids, organic chlorides, etc. Toxic waste from industries can result in serious contamination of our drinking water and the air we breathe. Environmental Protection Agency Superfund sites are extreme examples of industrial pollution [5].

In the past, the emphasis was on waste treatment to mitigate the impact on the environment. These are called the end-of-pipe methods. Now it is recognized that waste represents unused materials/additives and thus, for economic and environmental reasons it is in the interest of the industrialist to minimize it through process optimization or redesign to develop cleaner manufacturing processes.

1.2 What does "sustainable manufacturing" mean?

There have been many studies of sustainable development, but fewer specifically on sustainable manufacturing. The Brundtland Commission defined sustainable development in 1987 as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [6]. Sustainable manufacturing refers to developing and practicing technologies to transform materials with reduced energy consumption, reduced emission of greenhouse gases, reduced generation of waste, and use of non-renewable or toxic materials [7].

Sustainable manufacturing includes the integration of processes, decision-making and the environmental concerns of an active industrial system to achieve economic growth, without destroying precious resources or the environment. Sustainability applies to the entire life cycle of a product. It involves selection of materials, extraction of the materials, manufacture of component parts, assembly methods, retailing, product use, recycling, recovery, and disposal. Some examples include

- Develop products that last longer or have extended service lives
- Re-design or reformulate products to use easily recyclable materials
- Substitute toxic with non-toxic materials in manufacturing processes
- Improve manufacturing technology, equipment, materials, tools, and operations to minimize environmental impacts
- Adopt cleaner production technologies to reduce waste, better manage industrial waste, and maximize recycling
- Develop technologies to reduce energy consumption, recover waste heat, and use renewable energy sources, such as solar, wind, bio-mass, landfill, and digester gases
- Develop reusable packaging products

The practice of sustainable manufacturing has also significant social implications. Some of the measures that indicate a level of sustainability are worker health and safety, labor union roles, worker rights, child labor protections, gender equality in the workplace, absence of nuisance factors (such as industrial noise and negative visual impact), the company's involvement in, and acceptance by the community. Other measures may include the company's impact on the quality of life in the local area; e.g., population density, employment level, educational resources, housing, poverty, crime, nutrition, sanitation, healthcare facilities, and infant mortality [7].

Social responsibility for manufacturing industry generally goes beyond that required by statutory obligation. Companies can improve their reputation by practicing sustainable manufacturing. With the increasing awareness and concern for the environment by the general public, it could result in an improved marketplace and increased sales for the company. Sustainable manufacturing can also create goodwill with investors, communities, and regulators.

1.3 Benefits of Modeling and Simulation

Modeling and simulation technologies hold tremendous promise for reducing costs, improving productivity and quality, and shortening the time-to-market for manufactured goods. The U.S. Department of Defense defines modeling as the:

"*application of a standard, rigorous, structured methodology to create and validate a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process* [8].

In [9], Jerry Banks defines simulation as:

"…the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of that artificial history to draw inferences concerning the operational characteristics of the real system that is represented. Simulation is an indispensable problem-solving methodology for the solution of many real-world problems. Simulation is used to describe and analyze the behavior of a system, ask what-if questions about the real system, and aid in the design of real systems. Both existing and conceptual systems can be modeled with simulation."

Manufacturing simulation focuses on modeling the behavior of manufacturing organizations, processes, and systems. Organizations, processes and systems include supply chains, as well as people, machines, tools, and information systems. For example, manufacturing simulation can be used to

- Model "as-is" and "to-be" manufacturing and support operations from the supply chain level down to the shop floor
- Evaluate the manufacturability of new product designs
- Support the development and validation of process data for new products
- Assist in the engineering of new production systems and processes
- Evaluate the impact of manufacturing on overall business performance
- Evaluate resource allocation and scheduling alternatives
- Analyze layouts and flow of materials within production areas, lines, and workstations
- Perform capacity planning analyses
- Determine production and material handling resource requirements
- Train production and support staff on systems and processes
- Develop metrics to allow the comparison of predicted performance against "best in class" benchmarks to support continuous improvement of manufacturing operations.

1.4 Overview of the Paper

In the context of this paper, the focus will be on simulation for discrete parts manufacturing. Some examples of discrete parts manufacturing include the aerospace, automotive, appliance, and electronics industries. Industries not addressed in this discussion include continuous process manufacturing such as chemical, steel, and food processing. The remainder of this paper focuses on how simulation technology could help industry to achieve sustainable manufacturing goals and what actions need to occur to reach those goals. Section 2 discusses current manufacturing simulation case studies and their shortcomings from the sustainability perspective. Section 3 presents key aspects of a new technical approach to simulation for sustainable manufacturing i.e., changes to simulation case study objectives; changes to simulation evaluation metrics; and changes to software tools, interface standards, and reference data sets. Section 4 provides conclusions for the information presented in this paper.

2. Manufacturing Simulation Today

The primary reason for building manufacturing simulations is to provide support tools that aid the manufacturing decision-making process. Simulations are typically a part of a case study commissioned by manufacturing management to address a particular set of problems. Simulation case studies are conducted to analyze and improve the efficiency and effectiveness of manufacturing organizations, systems, and processes. Studies are designed to solve specific problems and get answers to specific questions. Studies often model some aspect of current operations and validate the effect of some hypothetical change(s) to those operations. The performance of current and proposed systems is evaluated according to some set of metrics. If the simulation validates that sufficient improvements can be expected, then the proposed changes are implemented.

Simulation case study objectives define the reasons for performing the simulation. The objectives of the case study determine the types of simulation models, input data, and output data that are required. Some examples of study objectives might be to evaluate the best site for a new plant, create a better layout for an existing facility, determine the impact of a proposed new machine on shop production capacity, or evaluate alternative scheduling algorithms. High-level study objectives can be further decomposed into individual questions that may be answered directly from simulation results. If the study objective is site selection, one question might be: Which site would result in the lowest expected overall operating costs given several different projected levels of production for a selected set of products?

2.1 The Simulation Study Process

Simulation textbooks typically recommend that a ten to twelve step process be followed in the development of a case study and associated simulation models. The recommended approach usually involves the following steps: (1) problem formulation, (2) setting of objectives and overall project plan, (3) model conceptualization, (4) data collection, (5) model translation into computerized format, (6) code verification, (7) model validation, (8) design of experiments to be run, (9) production runs and analysis, (10) documentation and reporting, and (11) implementation [10]. Unfortunately, this approach often leaves considerable work and possibly too much creative responsibility to the simulation analyst.

Using this approach, the process of defining models and constructing simulations is perhaps as much an art as it is a science. Simulations are often developed from scratch, so the skill of the individual analyst may figure significantly in the quality of the results that are obtained. There is little opportunity for the analyst to build upon the work of others since each simulation is built as a custom solution to a uniquely defined problem. Input data from other manufacturing software applications is not often in the format required for simulation, so data must often be abstracted, reformatted, and/or translated. Furthermore, pressure from manufacturing management to obtain quick results may have a negative impact on the performance of the simulation analyst and the quality of results obtained.

Simulation studies are often conducted to analyze and improve the efficiency and effectiveness of some aspect(s) of a manufacturing system - sustainability has not often been the focus of these studies. Common objectives of simulations include estimation of production costs; validation of production/support processes and data; scheduling support; line balancing; product mix, resource, and capacity analyses; layout, work measurement, and ergonomic analyses; planning for equipment breakdowns, maintenance, rejects, and rework; and visualization of new systems. Outputs and results of simulations include equipment, labor, and tool utilization; work throughput; lead time requirements, operations timing, tentative schedules, and expected completion dates; material utilization and inventory level data; and cost data.

Figure 1 shows an example of a simulation that was developed at NIST to model the manufacturing process for a handheld power tool. Simulation objectives included the layout of the production line and workspaces, validation of assembly process sequences, inventory replenishment planning, line balancing, and visualization of the overall production system [11]. Sustainability issues were not a priority at the time that this simulation was developed.

2.2 Simulation Shortcomings

As it is generally practiced today, simulation in discrete parts manufacturing seldom addresses sustainability issues. There is very little published research where manufacturing simulation includes environmental concerns or parameters in the modeling process. Some of these examples will now follow. It is to be noticed that these cases only address a narrow aspect of manufacturing sustainability and are mainly conducted using existing simulation tools or a minor enhancement of the modeling. Russell et al. [12] incorporate environmental issues in a filament winding composite manufacturing system simulation. The researchers present a system called SimBuilder, which can output six reports including scrapped materials and cost at each workstation; the overall quantities of materials scrapped as waste; and energy report which includes the amount and cost of energy used. A simulation model of an Aluminum smelter plant where two equipment maintenance policies are simulated to evaluate which is more environmentally friendly from a pollution perspective is presented in [13]. Kumazawa et al. [14] describe a business model of a vacuum cleaner, which takes into account the collection and re-use of the discarded product. The manufacturer bears the collection cost under the Extended Producer Responsibility (EPR) system. Different scenarios representing different levels of collection and product design are evaluated. The objective is to minimize overall costs. Turon et al. [15] also report on simulation modeling research to evaluate the effect of process redesign on material and water consumption in a coated paper mill. However, all such examples do not tackle the overall wider concern of the concept of sustainable manufacturing.

Many manufacturers, especially small ones, do not even use simulation for currently intended uses due to lack of resources; i.e., software, skilled analysts, and accessible data and time pressures. Simulation “what if” analyses, when performed, typically focus on streamlining and validating processes, reducing costs, and meeting schedules; not the identification and evaluation of environmentally friendly alternatives.

Simulations are not typically used to experiment with different operational policies or decision making where the main objective is to find the optimal consumption of energy resources or the minimal emission of waste. Current simulation products do not typically support the modeling of environmental concerns or impacts; e.g., energy consumption or carbon footprint, waste/hazardous materials disposal, and pollution. The types and quantities of manufacturing waste associated with manufacturing processes are not often a simulation consideration. Simulations typically do not model the by-products of manufacturing, generation of effluents, or their disposal. Information on alternative manufacturing technologies, processes, and data is not readily available to the simulation analyst to incorporate into models. Effects of good housekeeping on the reduction of waste and pollutants are not supported. Similarly, regional differences in environmental safety requirements are not represented in simulation environments. Occupational

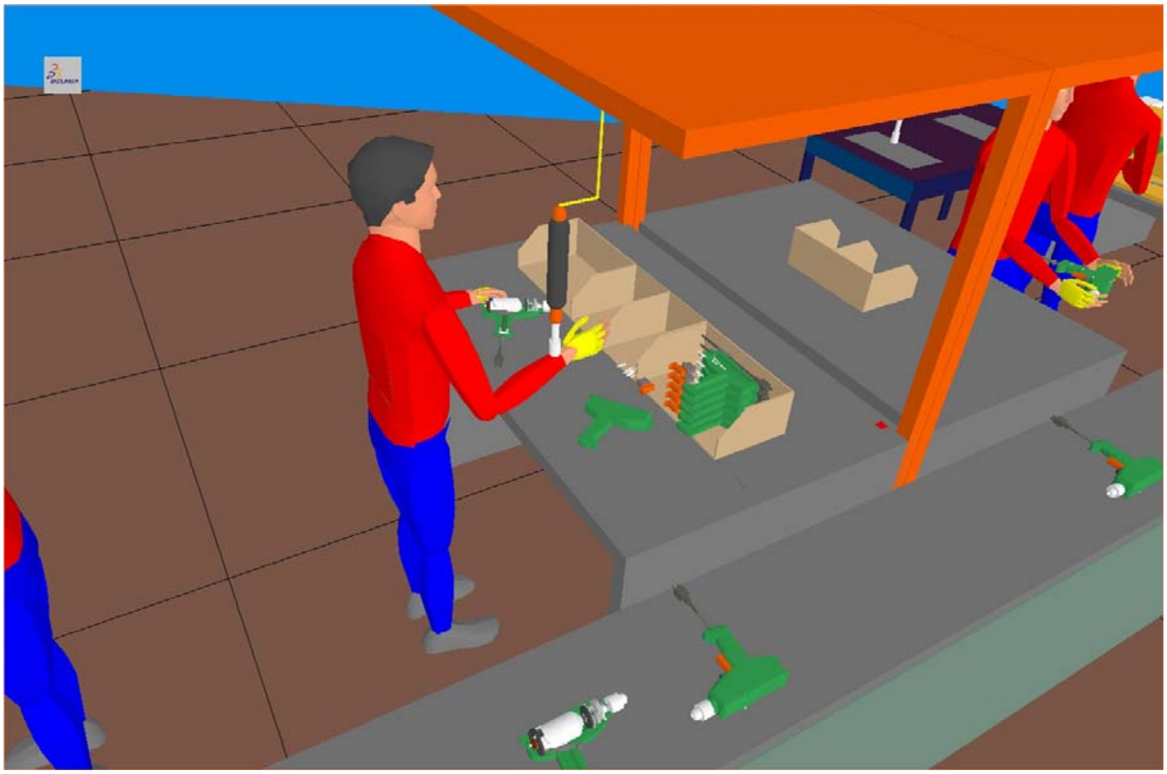

Figure 1. Simulation of the assembly of handheld power tools

safety and health considerations may not be accounted for in process models. Recovery, recycling, and life cycle costs (LCC) of materials are often not addressed in design and manufacturing simulations. Simulations usually do not deal with the usage and disposal practices of product users after sale. These issues are not modeled today because of the way the manufacturing simulation systems were developed and evolved. These systems were modeled to help a company to meet design and production objectives. No effort had been put into including sustainability constructs within the systems. Currently, simulation is still not that widely utilized because of high cost and time required. If sustainability constructs are to be included in simulation models, additional programming may be required that further complicates or increases the modeling effort.

3. Simulation for Sustainability

To support sustainability, a number of changes will need to be made in industry's approach to manufacturing simulation. The three major change areas are

- Simulation case studies
- Evaluation metrics
- Tools, standards, and data sets

Changes will need to be made to the way simulation case studies are performed - new objectives will need to be addressed. The metrics by which we evaluate simulation results will need to change to incorporate the scoring of sustainability factors. Finally, the software applications used to build simulations must be enhanced to incorporate new functionality. New data standards and reference data sets will be required to provide ready access to appropriate sustainability reference data.

3.1 Changes to Simulation Case Studies

A framework for modular manufacturing simulation is outlined in [16]. One dimension of this framework is the identification of various types of manufacturing simulation case studies. In the past, the objectives of these case studies have focused on enhancing manufacturing operations, for example, shortening lead times, reducing production costs, and improving product quality. When sustainability enters the picture, the scope of many case studies will need to be expanded to address additional concerns such as the environmental impact of manufacturing operations. Examples of traditional and sustainable case study objectives are described below.

Market Forecast Case Study

Traditional - Model past, present, and future economic and market trends to forecast future demand, expected product sales, and estimate required production levels.

Sustainable - Use market forecast models and data to determine and anticipate lifecycle impacts to support planning for the best product support, recycling, and recovery strategies.

Supply Chain Case Study
Traditional - Model order processing, engineering, fabrication, assembly, warehousing, inventory, and transportation activities and information flows to determine lead times, schedule orders, plan inventory levels, coordinate operations, and optimize performance of a supply chain and meet customer performance requirements.
Sustainable - Model energy consumption across the supply chain to minimize carbon footprint, pollution, unnecessary transportation (coordinate deliveries to avoid traffic congestion); use preferred environmentally friendly suppliers; and, level production schedules to avoiding layoffs.

Site Selection Case Study
Traditional - Evaluate the cost and expected performance of a manufacturing plant or facility given different projected operating levels at various sites based on differences in the cost of real estate, transportation, utilities, labor availability, etc.
Sustainable - Evaluate factors such as the ability of the site to use renewable energy resources (e.g., solar or wind power), impact on local environment and community (e.g., traffic, noise, air, and water pollution), and accessibility to interdependent facilities and services (e.g., public transportation for employees).

Business Process Case Study
Traditional - Model the flow and sequence of business processes, events, conditions on users and organizational units to optimize overall system performance through the reduction of bottlenecks, duplicate, and non value-added activities.
Sustainable - Model new sustainable business practices to consider when changes may be implemented to adopt clean manufacturing processes, use renewable energy and resources.

Scheduling Case Study
Traditional - Evaluate the effects of changes to scheduling policies and algorithms on operational cost, performance, throughput, etc.
Sustainable - Evaluate the effect of production schedules and the timing of work so as to coordinate activation of equipment, and consider effects of time of day energy usage, flexible employee work schedules, traffic congestion minimization, waste reduction (materials whose usage is time sensitive), noise generation, and atmospheric pollution (high ozone days).

Plant Layout Case Study
Traditional - Evaluate the effects of different layout configurations on production systems performance, floor space requirements, material handling costs, buffer storage requirements, throughput, interactions between systems (vibration, heat, cleanliness issues), etc.
Sustainable - Evaluate effect of layout on machine and equipment utilization and energy use (through reduction of idle time), operational and maintenance accessibility, house keeping and worker health and safety.

Capital Equipment Case Study
Traditional - Develop models of production operations with changes to capital equipment configurations to evaluate changes in production capacity and operational costs to address efficiency, cost, and quality issues.
Sustainable - Consider additional sustainability issues when evaluating the replacement of equipment and associated tooling.

Work Force Case Study
Traditional - Determine effects on operational costs of changes in workforce including modifications to employee skill levels, work calendar, shift schedules, layoffs, use of contract workers, absenteeism, etc.
Sustainable - Address sustainability issues in workforce modeling; i.e., community interests, diversity, education, benefits, trainee programs, flexible schedules, and traffic congestion.

Product Mix Case Study
Traditional - Evaluate the effects of changes of product mix on performance including cost of operations, capacity, resource utilization, schedule, etc.
Sustainable **–** Determine effects of product mix on energy usage, materials, and waste.

Capacity Analysis Case Study
Traditional - Develop models of existing and projected workloads to determine available (unused) capacity of production and support resources.
Sustainable - Evaluate effect of changing to sustainable processes on required capacity of production and support services.

Line Balancing Case Study
Traditional - Model changes in production line performance, throughput, cycle time, etc. due to changes in the line configuration, assignment of operations, and workers on the production line.
Sustainable - Consider tradeoffs of worker job satisfaction on cycle time and job assignments versus line efficiency.

Cost Estimation Case Study
Traditional - Model production operations for a product or order to generate expected labor, material, and processing costs.
Sustainable - Incorporate sustainability costs and benefits in estimation processes.

Process Validation Case Study
Traditional - Model the execution of manufacturing plans, control programs, methods, work instructions, and processes to validate that data is correct and will produce expected results.
Sustainable - Evaluate additional factors such as energy consumption, use of alternative environmentally friendly

processes, minimization of the use of harmful chemicals or pollutants, and noise reduction.

Process Capability Case Study
Traditional - Model systems to determine whether production capabilities are sufficient to meet process requirements including the use of statistical process control techniques to determine whether processes can be kept in control range.
Sustainable - Determine if the shift to sustainable equipment, processes, and materials will have an effect on process capabilities.

Ergonomic Analysis Case Study
Traditional - Evaluate ergonomic aspects of worker tasks for efficiency of operation, theoretical production rate, risk of injury, rest requirements, etc.
Sustainable - Place greater emphasis on safety, exposure to hazards, injury prevention mechanisms, long term health issues, task diversification, job satisfaction, and employee morale.

Inventory Case Study
Traditional - Evaluate impact on system performance, reduction of work-in-process, and carrying costs due to changes in inventory management policies. Policies include inventory size, location, allocation strategies for storage areas, reorder point and safety stock levels, Just-in-Time (JIT) delivery from suppliers, security systems, inventory tracking mechanisms, etc.
Sustainable - Consider tradeoffs between more frequent replenishment and its negative effects; i.e., increased energy consumption and traffic congestion due to more frequent replenishments.

Material Handling Case Study
Traditional - Model the effects of changes to material delivery, storage and retrieval systems, shipping and receiving, kitting stations, etc. on such issues as performance and operational costs.
Sustainable - Identify strategies for minimizing material movements, use of reusable containers and packaging, and environmentally friendly handling systems.

Maintenance Case Study
Traditional - Model the effects of changes in preventive maintenance schedules on breakdowns, time to repair, maintenance personnel requirements, availability of repair parts, maintenance costs, and equipment reliability on the overall performance of the plant and cost of operations.
Sustainable - Develop more conscientious maintenance programs for production and support equipment, HVAC systems, and work areas so as to reduce outputs of pollutants and maintain clean safe work environments.

3.2 Changes to Evaluation Metrics

In the previous section, the notion of changes to simulation case study models to support sustainability objectives was introduced. Another change that is needed is to the metrics that simulations generate.

Some of the outputs of simulation case studies are various metrics that can be used to evaluate and compare "what-if" propositions. A metric is a simulation output measure of a process, operation, or system that is crucial to the evaluation of alternative solutions. In the past, metrics have focused on enhancing product quality, improving production efficiency, and/or reducing costs. In the future, additional metrics will be required to evaluate "what-if" propositions for sustainability. Possible sustainability metrics will measure energy consumption, types and quantities of material used, pollution, manufacturing waste and by-products, recycling, product reuse, worker health/safety, and other effects on the environment and the community. A table of the traditional metrics used today and new sustainability metrics for the future is presented in Table 1 below.

3.3 Changes to Tools, Standards, and Data Sets

Current simulation tools often provide functionality that helps engineers and simulation analysts model and validate manufacturing processes, work flow, schedules; introduce new products and processes; coordinate logistics operations across supply chains; determine material, labor, equipment, tooling, inventory, material handling, and maintenance requirements; plan for equipment breakdowns and repairs; analyze the ergonomics of manual tasks; and visualize manufacturing systems. The tools are concerned with helping the analyst reduce costs, minimize production lead times, and improve product quality. Commercial off-the-shelf simulation tools, for the most part, do not address sustainability. They do not usually measure energy consumption; track the by-products of manufacturing processes (e.g., pollutants or waste); evaluate environmentally friendly alternatives; or address any of a number of worker or community quality of life issues, as they pertain to manufacturing operations. In order 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.

Abstraction is an intrinsic part of the manufacturing simulation modeling process. In the development of a simulation, a manager, engineer, simulation analyst, or member of the production staff typically performs an abstraction process and creates a representation of the manufacturing system or process. This step is necessary because simulators typically provide very generic capabilities that must be adapted to specific problems. The abstraction process may involve observation, analysis, simplification, approximation, substitution, representation, and/or description. The outputs of this process are new conceptual representations or descriptions with the possible introduction of errors. The

Traditional Metrics	Sustainability Metrics
Efficiency • # jobs produced per unit of time • job flow, cycle, or manufacturing lead time • make span of a set of jobs • job queuing time • queue lengths • job transfer time • worker and equipment utilization • equipment downtime due to breakage, blockage or starvation • machine utilization • balance of equipment utilization • overall plant capacity utilization • time to market • job lateness • number of jobs tardy • proportion of jobs tardy • order lead times • travel distance for products and components • inventory turns • work-in-process • scrap and rework measures **Costs and returns** • cost of carrying raw materials and work-in-progress inventories • machine cost per unit time • material handling/transportation costs • labor cost • energy cost per unit time • total job completion cost • payback periods • return on investment in plant and equipment	**Energy use** • % of energy use that is renewable • energy use per unit of product made • energy cost per product unit • energy cost as % of total expenses • plant heating and cooling energy efficiency measures **Pollution** • emissions per unit of product output • effluents that are captured and treated • greenhouse gases that are captured and treated • cost of fines and charges due to pollution • carbon footprint of products and processes • noise level measures **Material usage** • % recycled/recyclable materials used • % environmentally-friendly materials used • output per unit of material used • output per units of water used • lifetime of materials used • environmentally-friendly packaging measures • paper process management measures **Waste** • quantity of waste produced per unit output • percentage of waste materials recovered • waste water recovery measure • costs to recover (and dispose or reuse) discarded product, if regulations impose so **Worker health and safety** • work-related accidents and injuries • ergonomics issues consideration in material handling and processing • healthcare costs due to occupational accidents • compensation costs due to work related injuries and suffering • worker job repetitiveness, satisfaction level, morale factors • lost work days due to injuries • lost production due to injuries **Community impact** • land usage, green space, etc. • traffic impact on local roads • use of public transportation by employees • rain water capture

Table 1. Traditional and Sustainability Simulation Metrics

abstraction process consumes considerable time and effort. It can be a major source of errors. To speed up the modeling process and help the analyst avoid errors, it is critical that simulation tools become more closely aligned with the real world systems, processes, and data that they are being used to model.

The development of neutral, vendor-independent data formats for storing simulation models and reference data could greatly improve the accessibility of simulation technology to industry by enabling the development of reusable models. Such neutral, simulation-model formats would enable the development of reusable models and reference data by individual companies, simulation vendors, equipment and resource manufacturers, consultants, and service providers. Model libraries could be marketed as stand-alone products or distributed as shareware. Reference data sets to support sustainability could also be developed to provide information on energy consumption, alternative processes and materials, pollution data, improved equipment capabilities, worker task analysis, job satisfaction evaluation criteria, material recycling and recovery opportunities, community impact, mitigation strategies, etc.

Neutral model formats would help enlarge the market for simulation models and make their development a more viable business enterprise. Standard formats for models would make it possible for simulation developers to sell model libraries much the same way clip art libraries are sold for graphics software packages today. Simulation model libraries could be expected to increase the value of manufacturing simulators for industrial users much the same way graphics libraries increase the value of photo processing, paint, and graphics illustration software packages to their users.

4. Conclusions

The negative environmental effects of manufacturing on the environment have resulted in an increasing interest in sustainable manufacturing. Simulation has been used as an effective tool in the past to improve manufacturing operations. There are a number of shortcomings in the traditional use of simulation modeling that make it unsuitable for application to sustainable manufacturing. To achieve sustainability, manufacturing simulation will need to change to address additional issues. This paper has identified a number of different types of manufacturing simulation case studies. It also provided examples of traditional as well as new sustainability objectives for each type of study. New metrics are also suggested, i.e., output measures that are used to compare simulation study results. Final recommendations include enhancements to simulation tools, needed interface standards, and reference data sets that will make it easier for analysts to build simulations that support sustainability decision processes in the future.

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