November 2010

Modeling, Simulation and Analysis for Sustainable Product Development

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Abstract

Simulation plays a critical role in the design of products, materials and manufacturing processes. Increasingly, simulation is replacing physical tests to ensure product reliability and quality thereby facilitating steady reductions in design cycles. However, with the current global environmental crisis, there are gaps in the simulation tools used by industry to provide reliable results from which effective and equitable decisions can be made regarding environmental impacts at different stages of product realization and life cycle. For sustainable manufacturing planning, enhanced modeling techniques are needed to understand and predict the sustainability aspects through design and manufacturing where technologies can be applied to transform materials with reduced energy consumption, reduced emissions, reduced generation of waste products, and reduced use of non renewable or toxic materials. In this paper, a holistic and systems approach to Sustainable Manufacturing Planning and Simulation (SMPS) is identified and presented in an effort to bridge the gaps in the simulation tools to incorporate aspects pertaining to sustainability across the product lifecycle. For SMPS framework we consider building upon the previously developed Systems Integration of Manufacturing Applications (SIMA) project at NIST. Based on a case study and discussions we aim to address the usefulness of research towards having a simulation reference framework, and corresponding information models to facilitate effective decision making using simulation at different phases of product lifecycle. In the course of the paper we also identify and propose potential areas of future research in this direction.

Keywords: *sustainable manufacturing, sustainable design, planning, simulations, systems approach, framework*

1. Introduction

Simulation is all-pervading in the industry and has proven to be a very effective approach for problem solving and optimization. It plays a critical role in the design of materials, manufacturing processes, and products. Increasingly, simulation is reducing the physical testing required to ensure process and product reliability and quality. For products, this results in fewer physical prototypes and shorter design cycles. Steady reductions in design cycles are crucial to remain competitive in a world where the pace at which new consumer products are being developed is ever increasing day to day, especially at a time of economic and environmental crisis. Despite these promising predictions for simulation, current research illustrates significant shortcomings and challenges in different areas. Overall, simulation in industry sees continuing growth while facing significant obstacles to meet its full potential. According to the Blue Ribbon Panel on Simulation-Based Engineering Science [1], simulation has yet to play a central role in important industrial and defense design applications. The reason is *that large-scale simulation typically does not enter into the design cycle until its later phases*. Model preparation, typically requires substantial amount of time and labor and to achieve the appropriate fidelity and accuracy months are taken to prepare a model. This may be followed by calibrated tests if the design is substantially different from previous designs.

Sustainable manufacturing [2, 3] has varying definitions depending on the context of discussion [See Appendix A]. It broadly implies the development of innovative manufacturing sciences and technologies that span the entire lifecycle of products and services to minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound. In this paper we limit ourselves in exploring how modeling and simulation can augment sustainable manufacturing, by facilitating decision making across difference stages of product realization and lifecycle.

Law and McComas [4] reported that one of the primary application areas for modeling and simulation is in the area of manufacturing systems. In the literature, detailed discussions on modeling and simulation can be found in numerous books, among them Banks et al. [5] and Law and Kelton [6] are well known. The technology of utilizing discrete event simulation (DES), in particular, has been popular for numerous purposes other than manufacturing, such as patient flows in healthcare, military strategies, logistics, call centers and restaurants. Today sustainability considerations are increasingly relevant and require greater attention as industry needs to access the resource use increases. However, analysis and optimization of multiple objectives is not common in manufacturing simulation. DES in combination with Lifecycle Assessment (LCA) data is one possible approach for analyzing the cause and effect of various scenarios where time, resources, place, and randomness determine the outcome and being sustainable is considered crucial. For such analysis only a few research publications exist: Solding and Petku [7] and Solding and Thollander [8] both describe how DES can be utilized to lessen the electricity consumption for foundries. Ostergren et al. [9] and Johansson et al. [10] describe how DES can be

utilized in combination with LCA for quantifying environmental impacts during food production. Based on the literature review, Table 1 summarizes the roles and the corresponding gaps in simulation for sustainable manufacturing. Table 2 correspondingly summarizes the manufacturing information and tool related problems with respect to simulation for sustainability.

Table 1 Simulation for sustainability: roles and gaps

Roles	Gaps (resulting from a lack of)
• critical role in the design of products, materials and manufacturing processes	• metrics regarding sustainability • integration between design and simulation tools

• facilitates steady reductions in design cycles	• support for sustainability in the simulation tools
	  - reliable results from which effective and equitable decisions can be made regarding environmental impacts
	• enhanced modeling techniques
	  - ability to understand and predict the sustainability aspects through design and manufacturing where technologies can be applied to transform materials

Table 2 Sustainable manufacturing simulation: information and tool related problems

Information related problems result from a lack of:

- models that support simulation for sustainable product planning
- product-process-resource integration for simulation
- reference model for to identify and retrieve appropriate information
- interfaces between requirements-design, manufacturing and execution planning
- reasoning and decision support

Simulation tool related problems result from a lack of:

- integrated manufacturing planning and simulation
- characterization of manufacturing process resources
- integration of sustainability indications between tools
- extension beyond discrete event simulation
- sustainability metrics and indicators

With reference to DES, one of the key challenges is to define concepts and tools to incorporate attributes and metrics for various sustainability aspects in manufacturing enterprises. Case studies that incorporate sustainable manufacturing parameters for simulation need to be identified, including the evaluation metrics that incorporate the scoring of sustainability factors. Research efforts are also required to determine additional

functional capabilities, validated sustainability reference data, and new information models to cater to the new challenges. But in order to realize SM, industries need an reference integrated framework, quantifiable measurement techniques and appropriate performance metrics to objectively evaluate all aspects of sustainable manufacturing (including energy efficiency, emissions, key process technologies, modeling and simulation, and standards) necessary to meet expected regulatory requirements. Research and development of new measurement methodologies and assessment technologies of product and process performance are also crucial to ensure sustainability in manufacturing.

The subsequent paper is organized as follows: in section 2 we present an initial simplified framework for sustainable manufacturing planning and simulation. Section 3 then discusses the scope of research primarily in two directions: a) integrated manufacturing planning and simulation and b) information models that support such integrated manufacturing planning and simulation for sustainability. In section 4, we discuss a case study to show how manufacturing simulation can help decision support across various tiers promoting sustainability. Finally in Section 5 we present our conclusions and the scope for future work.

2. Sustainable Manufacturing Planning Methodology

Our initial objective is to develop a holistic and systems approach to Sustainable Manufacturing Planning and Simulation (SMPS). Problem solving using a holistic, systems or concurrent engineering is not new and has been widely reported in the literature. What is new is the focus on sustainability. Figure 1 presents a simplified illustration of the proposed approach to SMPS. We draw inspirations from the earlier Systems Integration of Manufacturing Applications (SIMA) project at NIST. To set the stage, we represent the different phases of product realization namely design product, engineer manufacture of the product, engineer production system and produce products as planning tiers. Visualizing then as tiers further helps us understand how simulation results can be useful within and across these tiers. From Figure 1, the first tier represents the design of the product, the second is engineering the manufacturability of the product, and the third is the engineering the production system or manufacturing planning. The last phase is the actual production execution. Figure 2 presents a detailed view of the tiers with corresponding high level product realization activities. The figure additionally shows sustainability related information flow across the tiers. Figure 3 shows the corresponding SIMA manufacturing activity model reproduced from [11]. For details on the corresponding activity models within each tier, please refer [11].The following sub-sections briefly discuss the individual tiers.
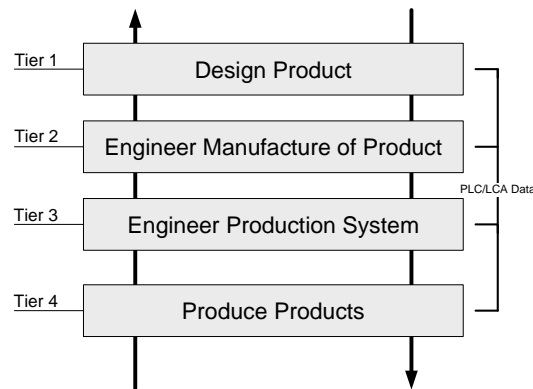
Figure 1. Typical stages in sustainable manufacturing planning and simulation

2.1 Design Product

When designing products, designers must cater for a multitude of technical, economic, social, environmental, and political requirements among others. This phase helps identify and conceptualize a marketable product, and create the complete description of it. With today's growing concerns for green products and green manufacturing, generating the right product and manufacturing specifications poses significant challenge. The activities in this phase as described in [11] include:

A11: Plan Products
A12: Generate Product Specifications
A13: Perform Preliminary Design
      A131: Develop Functional Decompositions
      A132: Evaluate and Select Decomposition
      A133: Develop Preliminary Configurations
      A134: Consolidate Configurations
      A135: Evaluate Alternative Designs
      A136: Select Design
A14: Produce Detailed Designs
      A141: Design System/Component
      A142: Analyze System/Component
      A143: Evaluate System/Component Design
      A144: Optimize Designs
      A145: Produce Assembly Drawings
      A146: Finalize System/Component Design

In order to respond to the increased demand for sustainability in product realization one can embrace total quality management (TQM) [13] as a means of understanding certain rules of thumb for good design analysis and planning in sustainable product and process development. For example, while generating product or system specifications one can introduce design requirements, constraints and the notion of value-added design constraints

i.e., a constraint that favors improved resource utilization and reducing environmental impact. Value added constraints in general imply the addition of value to a product, process or service, with or without accompanying cost and price increases. Viewing them as value added design constraints provides the advantage of assigning weights for tradeoffs favoring specific constraints, sustainability constraints in this case.
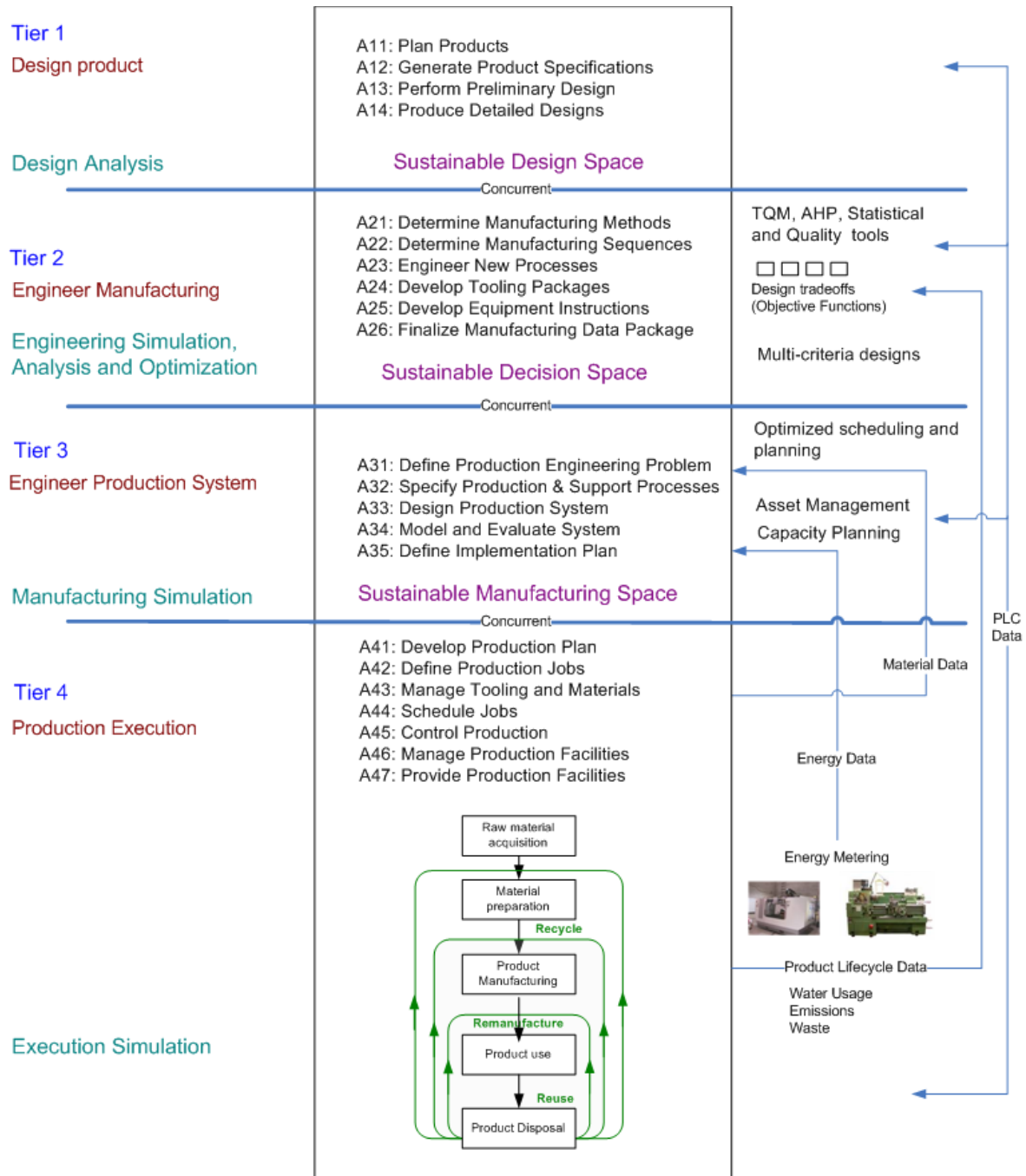

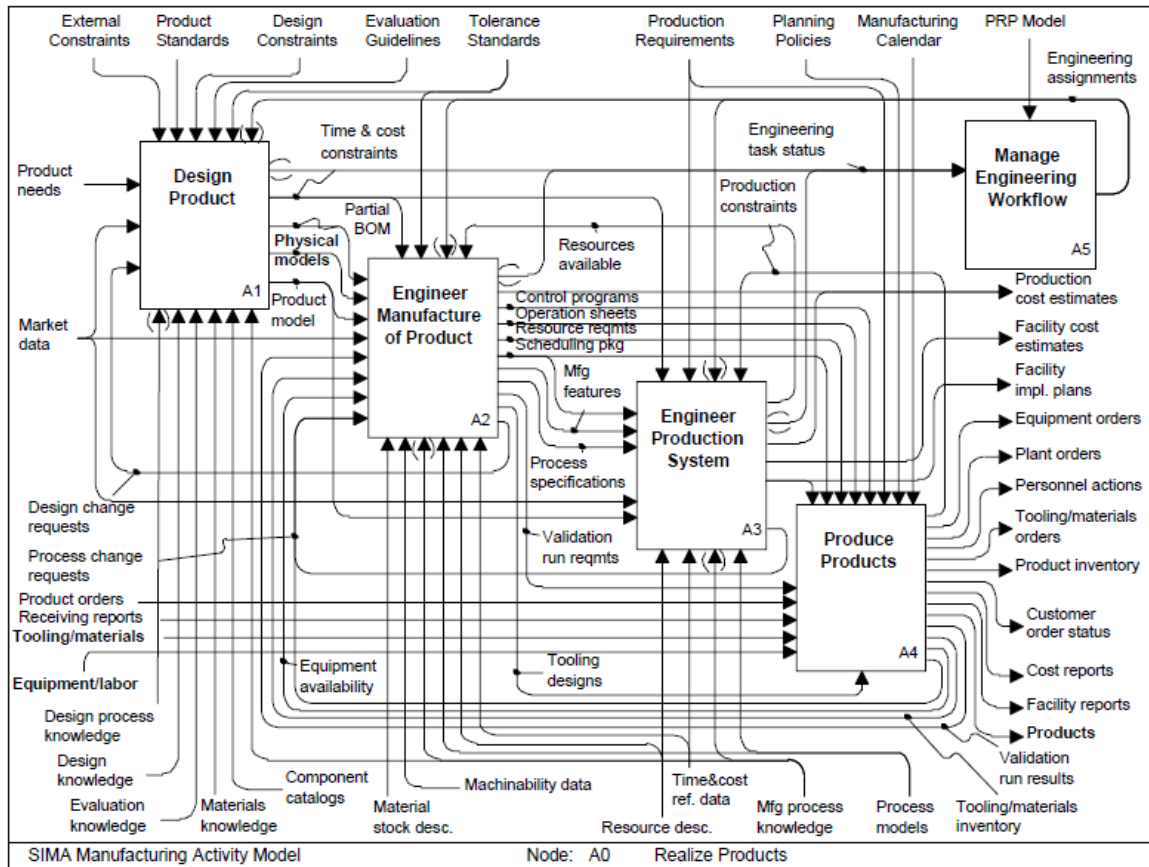**Figure 2** Integrated manufacturing planning and simulation

Figure 3 SIMA Manufacturing Activity Model: Realize products [11]

2.2 Engineer Manufacture of Product

This phase involves engineering the manufacturability of the product, i.e., defining the process of making the product, including the elementary stock materials and components to be acquired, the equipment, tooling and skills to be used and the details of that usage. Details include the exact sequence of setups and operations to be performed, and the complete instructions for each operation, whether by human or automated resources. By extension, the process of making the product includes measurement and inspection activities performed during production for process control and quality assurance. The activities in this phase as described in [11] include:

A21: Determine Manufacturing Methods
       A211: Derive manufacturing features
       A212: Select stock materials
       A213: Select processes
       A214: Select Major Resources
       A215: Develop Preliminary Cost Estimates
A22: Determine Manufacturing Sequences
       A221: Specify Operations

A222: Sequence operations
A223: Specify Part Routing
A224: Optimize & Validate Plan
A23: Engineer New Processes
A24: Develop Tooling Packages
A241: Select Tooling and Assemblies
A242: Design Tooling Assemblies
A243: Design Special Tooling
A244: Estimate Tooling Cost
A25: Develop Equipment Instructions
A251: Derive in-process work piece configurations
A252: Specify tooling requirements
A253: Generate Operator instructions
A254: Generate Machine Programs
A255: Validate equipment instructions
A26: Finalize Manufacturing Data Package
A261: Develop Final Cost Estimates
A262: Release Resource Package
A263: Release Scheduling Package
A264: Update Plan library

2.3 Engineer Production System

This phase involves the design of new or modified production facilities for the manufacture of a particular collection of Parts. A facility may be a plant, a shop, a line, a manufacturing cell, or a group of manufacturing cells. This activity encompasses both design-from-the-walls of such a facility and reengineering of all or part of such a facility to improve the production of certain products. It includes identification of the parts, products and processes for which the production system is to be tailored, identification of the equipment to be installed or replaced, (re)design of the floor layout, and development of an implementation plan for the (re)designed production system. The activities in this phase as described in [11] include:

A31: Define Production Engineering Problem
A311: Identify Project Type
A312: Identify Part Mix
A313: Identify Related Parts
A314: Identify Critical Dates
A315: Identify Target Costs
A316: Identify Manufacturing Constraints
A32: Specify Production & Support Processes
A321: Specify Process Requirements
A322: Specify Process Flows
A323: Specify Materials Flow Requirements
A324: Specify Support Systems Requirements
A33: Design Production System

      A331: Specify Production Equipment
      A332: Specify Control & Automation Systems
      A333: Develop Facility Layout
      A334: Design Information System
      A335: Integrate System Designs
A34: Model and Evaluate System
A35: Define Implementation Plan

2.4 Production Execution

This phase involves providing and maintaining the production facilities to produce the Parts according to the specifications in the process plans. This involves defining the production schedules and controlling the flow of materials into and out of the production facility, scheduling, controlling and executing the production processes themselves, providing and maintaining the production equipment and the human resources involved, developing and tracking the tooling and materials, etc. The activities in this phase as described in [11] include:

A41: Develop Production Plan
      A411: Create Master Schedule
      A412: Define Capacity Requirements
      A413: Create Production Orders
      A414: Monitor Production Orders
      A42: Define Production Jobs
      A421: Define Jobs
      A422: Generate Tool and Stock orders
      A423: Release Jobs
      A424: Monitor Job Completion
A43: Manage Tooling and Materials
A44: Schedule Jobs
      A441: Generate Job Schedule
      A442: Generate Operations Schedules
      A443: Generate Delivery Schedules
      A444: Track Jobs
A45: Control Production
      A451: Direct Personnel and Machines
      A452: Control and Monitor Jobs
      A453: Coordinate Equipment Groups
      A454: Control Equipment
A46: Manage Production Facilities
A47: Provide Production Facilities

During product realization, besides considering planning for the disposal (Reuse, Remanufacture and Recycle) of the part, it is equally important to consider the implications of sustainable manufacturing. Modeling and simulation of manufacturing processes can provide excellent opportunities in this regard. A well defined reference architecture can

support the ability to model and simulate product realization and end of life forecasts based upon historical trends of similar products, marketing programs and what-if scenarios. Such an architecture with reference to simulation can create opportunities for engineers to distribute cost, reliability, and environmental impacts of product manufacturing, component reuse, remanufacture, and recycling in such a way that the ends result is higher customer satisfaction than designing one product for all customer groups. More importantly, the analysis and simulation data accumulated across the various phases will support for equitable decision making.

3. Envisioned reference architecture characteristics

The following are the envisioned system level model characteristics based on the on the SMPS framework:

- **Tiered approach:** The four tiers, separated by naturally-defined boundaries, help to clarify specific engineering activities while also enabling local optimization.
- **Concurrent planning:** the frame work supports concurrent planning and looping wherein data exchange takes places between the different tiers
- **Sustainability:** Key Performance Indicators are quantifiable measurements that are incorporated into a model supporting their consideration throughout the PLC and collectively reflecting sustainability conformance.
- **Systems approach:** to optimization: the framework, by its structure, provides a systems approach to problem solving, taking a holistic approach where all tiers work in concert
- **Boundaries:** the framework, between tiers and within tiers, allows for boundaries to be set for measurement, analysis, and improvement
- **Integrated life cycle assessment:** LCA data can be dynamically linked for real time information management and assessment
- **Model congruency:** SMPS congruence is the state achieved by the tiers interacting for a state of agreement resulting in either sustainable products, processes or procedures.
- **Standards Integration:** supports linking of relevant standards to framework to check on regulatory compliance

4. Research Directions

We discuss the scope of research in two directions: 1) Integrated manufacturing planning and simulation and 2) information models that support such integrated manufacturing planning and simulation for sustainability.

4.1. Integrated Manufacturing Planning and Simulation

By developing a reference SMPS methodology and corresponding implementation one can expect the industry to simultaneously deal with trade-off factors such as manufacturability, cost, and environmental impact among others. With reference to Phase 3 in Figure 3,

traditional production planning and control involves: forecasting, i.e. estimating the production demands using a horizon of a few months to a few years for long range planning, and production planning which is matching needed production to available resources. Today, with energy cost representing a considerable amount of the total production cost, energy savings has become a major concern for manufacturing companies [16-18]. For example, on a factory floor with large production lines many machines may be operating at the same time, and hence the peak energy consumptions will be generally high, incurring high cost. To minimize setup times and support automation, companies rely heavily on computer aided process planning (CAPP) [19-21] along with other manufacturing information systems to meet production queues. While cost, quality and lead time are the typical performance indices for manufacturability assessment in CAPP, introducing additional sustainability indices such as energy efficiency can result in desirable alternative plans [22].

Through integrated production planning and simulation one can expect to expedite both the top-down and bottom-up approaches to facilitate better decision-making. Figure 5 presents an exploded view of different manufacturing processes, sub-processes, and further going into the details at the individual equipments. The idea behind Figure 5 is to show how sustainable indicators and corresponding values can be aggregated from the machine level to a factory flow, or further aggregated to the plant level. In the engineering production system phase (Phase 3), one must be able to answer questions like which production plan best utilizes the facility's capabilities? which plan is most energy efficient? which is an optimal scheduling plan? or which are the energy efficient machines? Note that the proposed approach allows for answering questions at both a macro and micro level (e.g. manufacturing process level versus machine level). The immediate challenge, in terms of research, is how companies do this implementation and integration with other systems and what other technical and business areas can benefit from understanding energy usage. In manufacturing scheduling, it is often known well in advance what has to be produced. This can often lead to a near optimal schedule for all jobs, ahead of time. But these methods at the present time are not well enough developed to cater for the new trends in economic and environmental crisis.

Today, one of the important applications of simulation in manufacturing is discrete event analysis. Simulation is used to predict how complex systems will behave by incorporating functionality that incorporates random events, changing operating conditions and activities where many interactions are involved. Simulation typically involves developing a model that includes discrete stations and events that occur with some probability distribution. Simulation results are used to evaluate the modeled system based on machine utilization, lead time, down time, make-span, etc. Simulation is an effective tool when considering the effect of a change, comparing decision options, or refining a design. A well implemented framework would facilitate additional analysis and synthesis based on the overall improvement and asset management, in terms of environmentally friendly indices namely: manufacturing energy, cost vs. efficiency, time, material reduction, recyclability and reusability. As an example a discrete event simulation in Phase 3 could be useful to generate product specifications at Phase 1. The corresponding case study will be subsequently discussed in the paper.

To support sustainable manufacturing from a regulatory and compliance point of view, standards and inspection procedures must be studied and incorporated in the new simulation models for raw materials, manufactured part, production process parameters, including verification and calibration. ISO has established related standards addressing Environmental Management and specifically life cycle assessment [24-26]. Figure 6 presents an initial mapping of relevant data required at various levels of simulation. For example in Phase 1, it involves the mapping of the engineering data, tools and appropriate standards for manufacturing planning.
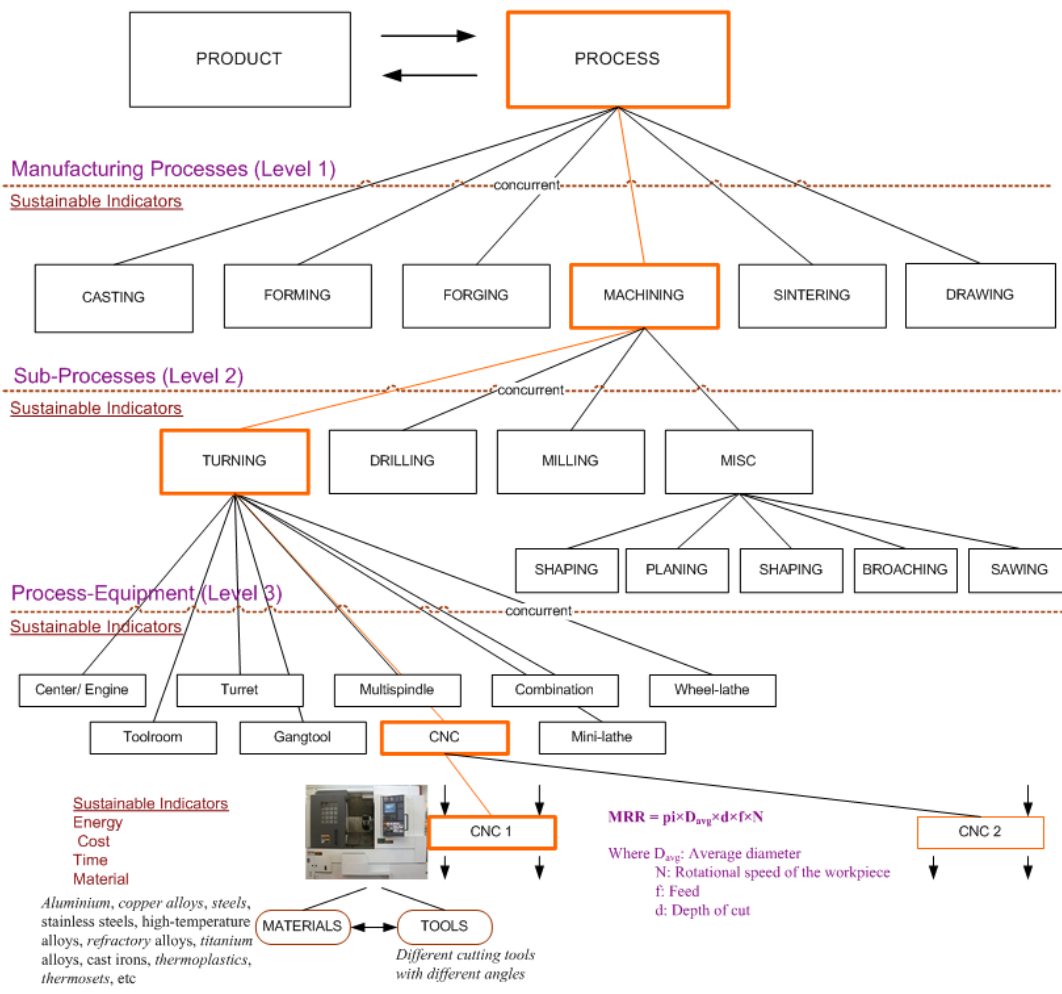

Figure 5 Manufacturing simulation (Phase 3)

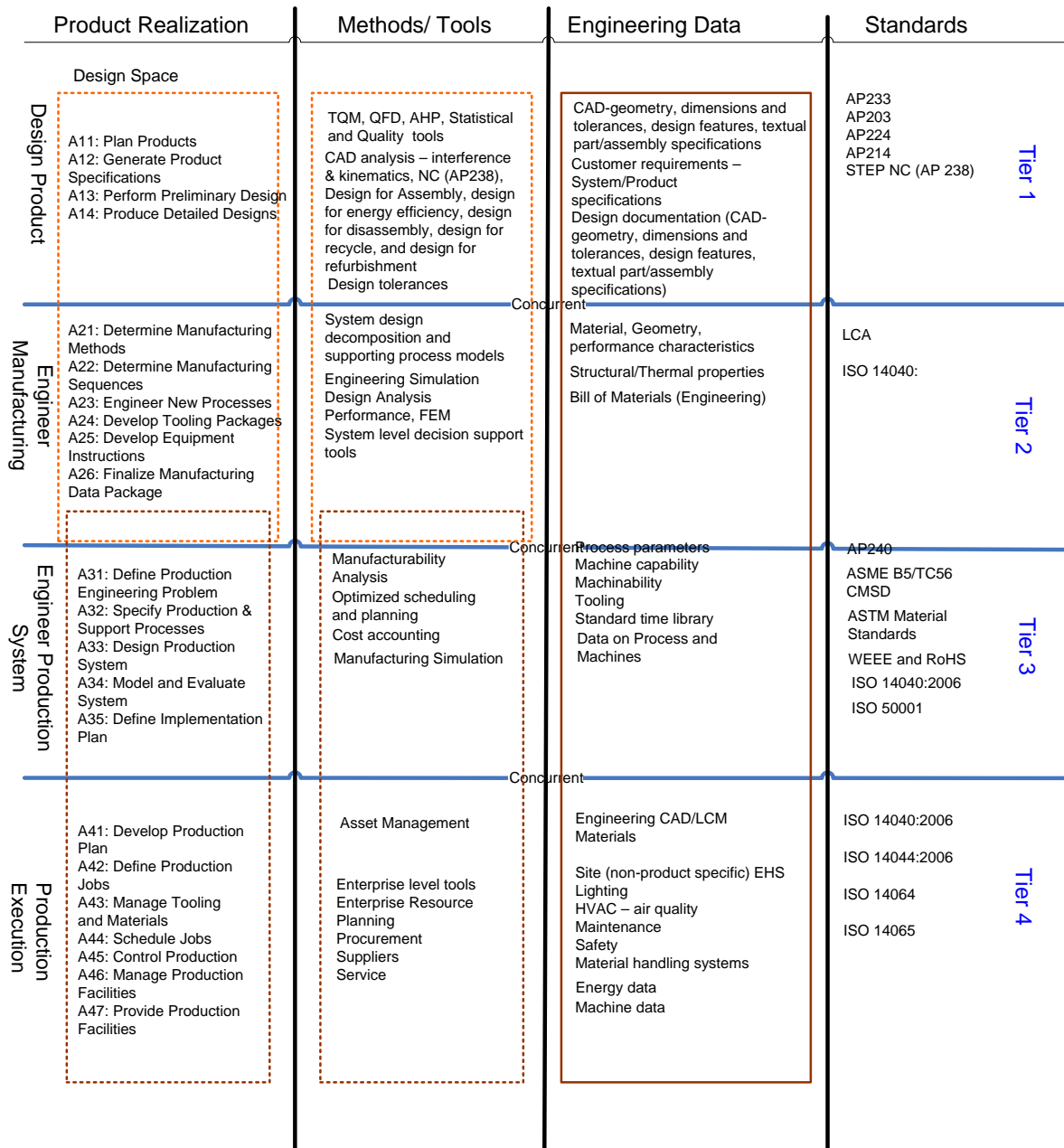|	Product Realization	Methods/ Tools	Engineering Data	Standards	
Design Product	Design Space A11: Plan Products A12: Generate Product Specifications A13: Perform Preliminary Design A14: Produce Detailed Designs	TQM, QFD, AHP, Statistical and Quality tools CAD analysis – interference & kinematics, NC (AP238), Design for Assembly, design for energy efficiency, design for disassembly, design for recycle, and design for refurbishment Design tolerances	CAD-geometry, dimensions and tolerances, design features, textual part/assembly specifications Customer requirements – System/Product specifications Design documentation (CAD-geometry, dimensions and tolerances, design features, textual part/assembly specifications)	AP233 AP203 AP224 AP214 STEP NC (AP 238)	**Tier 1**
			Concurrent		
Engineer Manufacturing	A21: Determine Manufacturing Methods A22: Determine Manufacturing Sequences A23: Engineer New Processes A24: Develop Tooling Packages A25: Develop Equipment Instructions A26: Finalize Manufacturing Data Package	System design decomposition and supporting process models Engineering Simulation Design Analysis Performance, FEM System level decision support tools	Material, Geometry, performance characteristics Structural/Thermal properties Bill of Materials (Engineering)	LCA ISO 14040:	**Tier 2**
			Concurrent		
Engineer Production System	A31: Define Production Engineering Problem A32: Specify Production & Support Processes A33: Design Production System A34: Model and Evaluate System A35: Define Implementation Plan	Manufacturability Analysis Optimized scheduling and planning Cost accounting Manufacturing Simulation	Process parameters Machine capability Machinability Tooling Standard time library Data on Process and Machines	AP240 ASME B5/TC56 CMSD ASTM Material Standards WEEE and RoHS ISO 14040:2006 ISO 50001	**Tier 3**
			Concurrent		
Production Execution	A41: Develop Production Plan A42: Define Production Jobs A43: Manage Tooling and Materials A44: Schedule Jobs A45: Control Production A46: Manage Production Facilities A47: Provide Production Facilities	Asset Management Enterprise level tools Enterprise Resource Planning Procurement Suppliers Service	Engineering CAD/LCM Materials Site (non-product specific) EHS Lighting HVAC – air quality Maintenance Safety Material handling systems Energy data Machine data	ISO 14040:2006 ISO 14044:2006 ISO 14064 ISO 14065	**Tier 4**

Figure 6 Initial mapping of relevant data required at various levels of product realization

4.2. Models that support simulation for sustainable manufacturing

Information management problems affect many aspects of manufacturing operations, but they are in particular a hindrance to the creation and reuse of manufacturing simulations. To be able to traverse across the different product creation phases information models that can support integrated planning and simulation (See Figure 6) are needed. The SMPS framework provides the opportunities to introduce sustainability factors to minimize

environmental impacts at various stages of the product lifecycle. To support the SMPS framework we envision a corresponding well connected information model to support efficient management of data from characterization to simulation for sustainable manufacturing and planning. We call the information model as a Reference Information Model. Figure 7 illustrates the concept of a reference information model. The idea behind such an information model is to provide not only the adequate points of reference for information across the different phases but also to provide a mapping and interface between them.
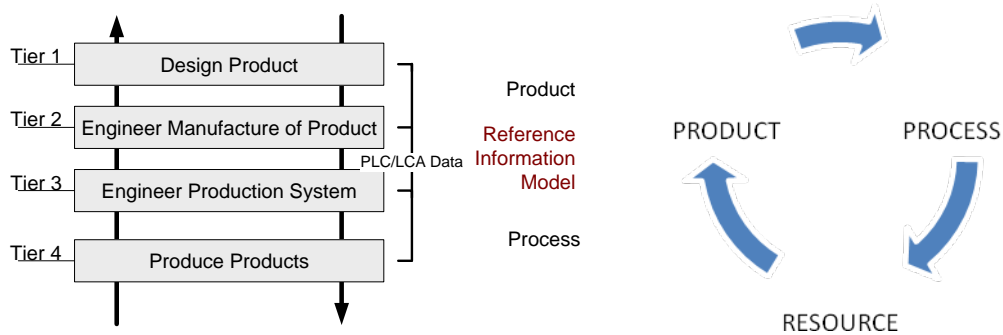
Figure 7 An information model that supports product-process-resource integration for Simulation

We envision that the new reference information model will facilitate the product-process-resource integration and facilitate tradeoffs and multi-criteria decision support for sustainable manufacturing. Figure 8 presents a simple landscape of relevant data and standards for enabling information exchange. As shown in Figure 8, the idea is to explore how the reference information model will provide the appropriate interfaces and links between the various data models and standards across the different planning stages. Table 5 in the Appendix presents some relevant manufacturing data related standards.

The idea behind the connecting lines in figure 8 is to show that different information models can be used at different stages of product realization yet a coherent mapping or reference information is vital for successful information exchange across simulation applications. The Y. axis shows the product, process and resource information models mapped across the different product realization stages on the X. axis.
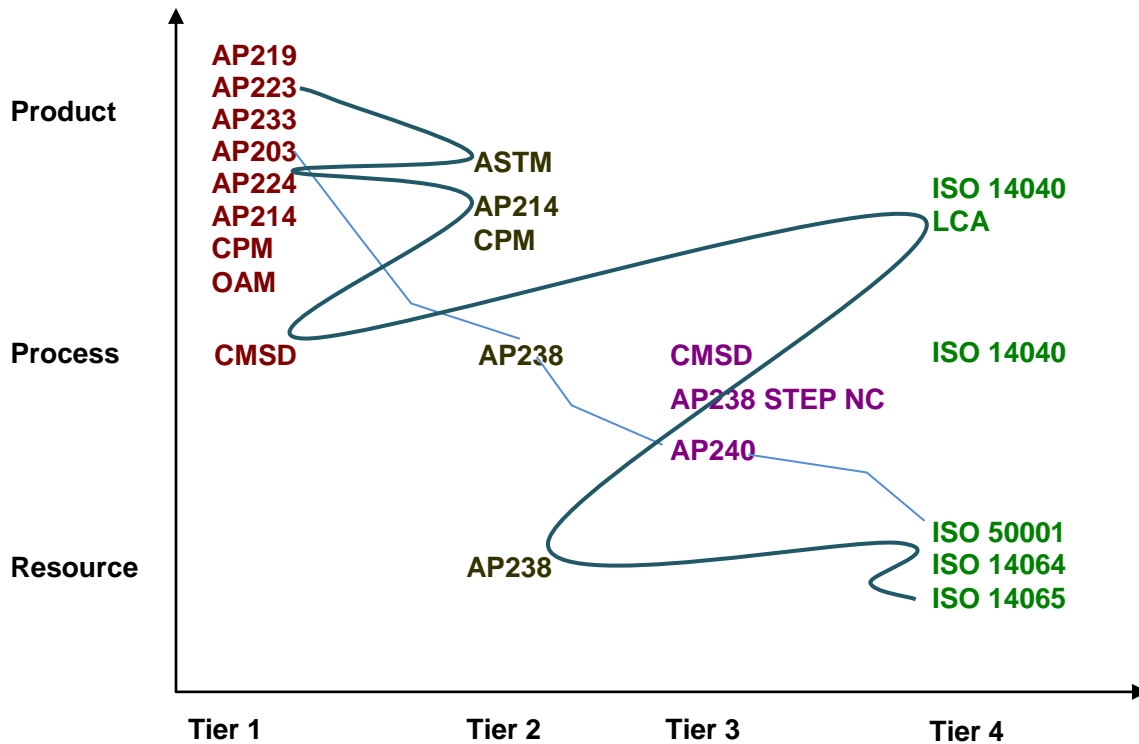
Figure 8 Landscape for enabling information exchange

There are number of useful implications one could envisage through sustainable manufacturing planning and simulation. Figure 9 presents the opportunities for manufacturing simulation, as means for analysis and optimization of machines and manufacturing processes to better implement sustainability strategies in an automotive manufacturing facility [27]. For example, energy efficiency trends of machines and manufacturing processes can be mapped and correlated.
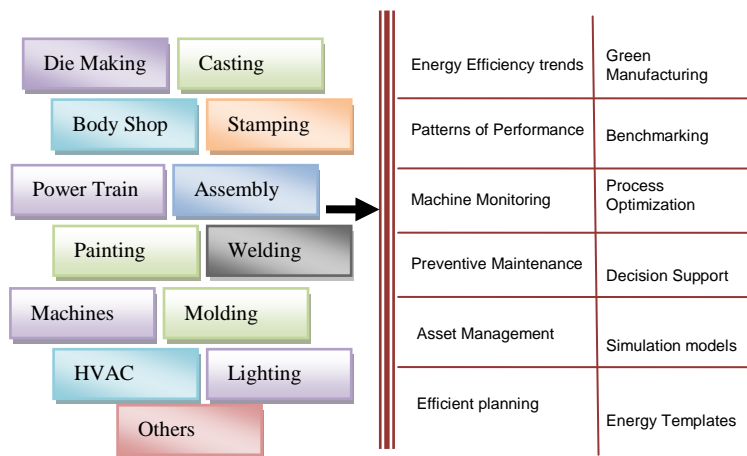
Figure 9 Implications of simulation models

5. Case Discussion

6.1. Industrial Scenario

To set the stage, consider simulating the energy utilization of a typical automotive manufacturing facility. Figure 10 presents the energy composite in selected automotive manufacturing operations [28]. The boundaries are marked in red to signal the energy losses in the energy infrastructure of the auto industry. Marked in yellow are the energy intensive manufacturing processes.
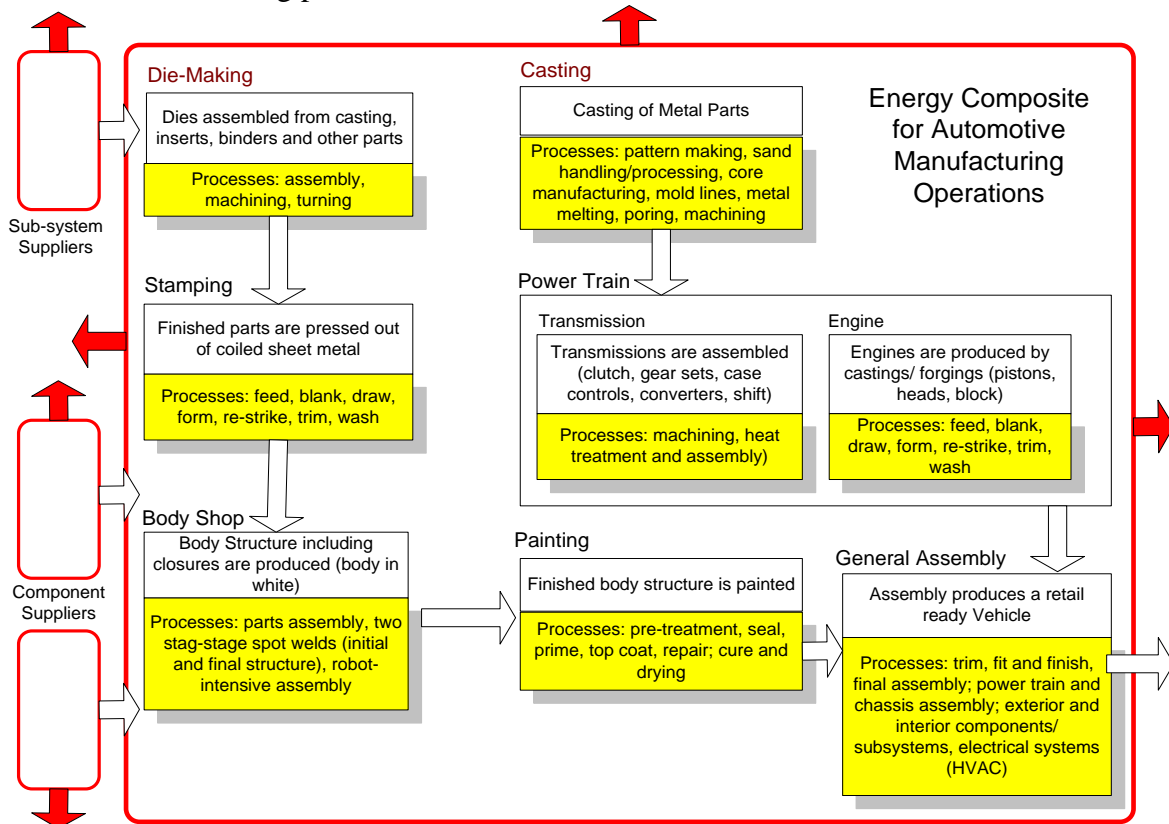

Figure 10 Energy composite for automotive manufacturing operations

Figure 11 below presents the corresponding breakdown of energy [42]. This is a rough estimate based on the on-site manufacturing processes while other subsystems and component suppliers are not accounted. Die-making and casting have been excluded because they are assumed to be captive operations (on-site) or out sourced and not included in the energy composite. There are multiple tests and inspection points that occur at various levels in between these operations. Further abatement occurs within all operations at some level.
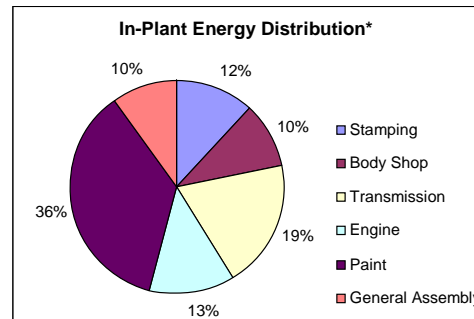
Figure 11 In-plant process energy distribution

From Figure 11, the paint shop consumes more energy than any other operation in the automotive industry. Within the paint shop, the conditioning of the air in the spray booths is the most energy-intensive process. Precise control of temperature and relative humidity in the paint booths are critical because it affects paint viscosity, or thickness which, in turn, affects the quality of the paint finish. Earlier, Bhattacharya from Honda [29], proposed a new control system that sets a tolerance window, provided by the paint supplier, rather than a fixed target. The new control system (knowledge based system), finds the temperature and relative humidity within that window that will require the least amount of heating, cooling or mist for humidity. It achieves energy savings by always directing the air to the least energy-intensive point within that tolerance window specified for production conditions. Figure 12 showing a snap shot of a paint shop simulation [30].
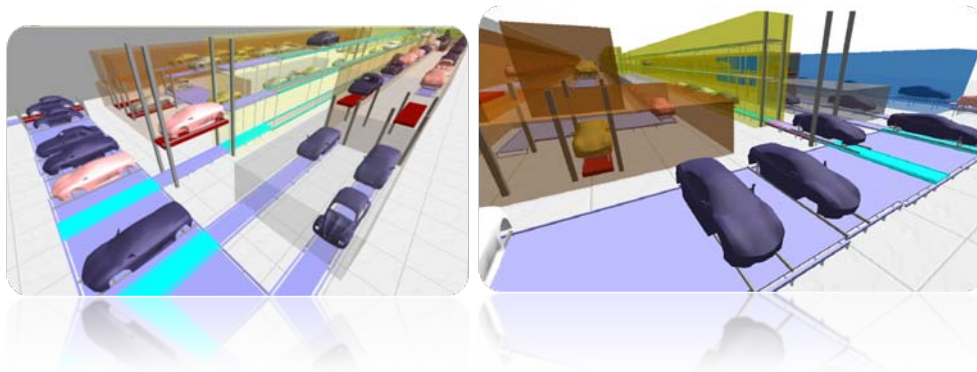

Figure 12 Paint shop simulation

The simulation tools used by industry must provide reliable results to cater for effective decisions towards sustainability and create opportunities to distribute the cost, reliability, and environmental impacts of energy use, emissions, waste, component reuse, remanufacture, and recycling in such a way that the end result is higher customer satisfaction. Since real-world phenomena are not deterministic, statistical methods that can quantify uncertainty will be needed. Considering design optimization, the constraints on the optimization of a product design relate to manufacturability, robustness, and a variety of other factors in addition to environmental sustainability. To be effective for engineering design, optimization methods must be closely coupled with simulation techniques.

6.2. 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 13. The work flow schematic was adopted and modified from [31]. This scenario presents a paint shop with six painting steps to set the scene for requirements in an automotive paint shop. In terms of the simulation integration architecture the case study is also intends to demonstrate how simulation in one phase can help with decisions in another. Here we show how DES in phase 3 can be utilized to generate design requirements or specifications for manufacturing systems in the early design stage (Phase 1) or at the manufacturing planning stage [32]. Requirement specification denotes the description of the behavior of the system to be developed. The case study develops a prototype paint shop model which incorporates the use of LCA data in combination with DES and supports alternate decisions on energy use, choice of machines, and environmental bottleneck detection.
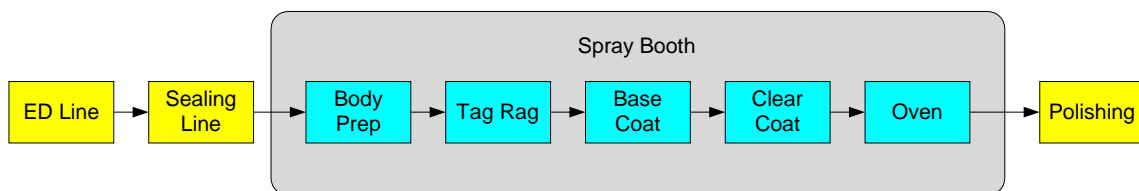

Figure 13 Example paint shop processes (adopted from Leng, and Yingchao 2005)

In Figure 3, the spray booth 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 [33-35] as seen in Figure 14.
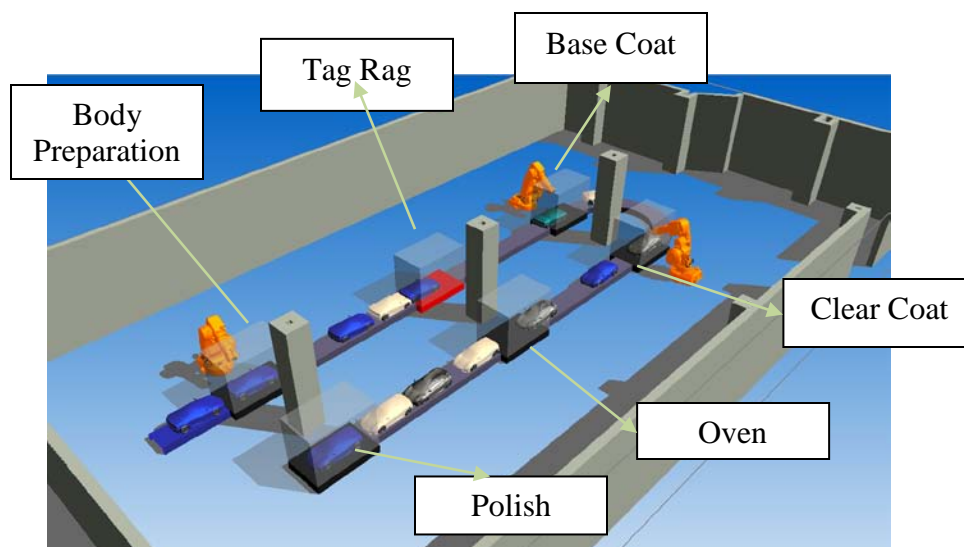

Figure 14 The 3D Simulation model of the paint shop

6.2.1. Input data to the Simulation model

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 3 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.

Table 3 Default settings for resources in the paint shop[1]

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

6.2.2. Case study Problem and Goal 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. In this case study, the goals of the sustainable manufacturing system are assumed as follows:

- to reach a production capacity of at least 50000 cars per year,
- there will be no more than metric 500 tons of CO_2 emission per year, and
- no new investment in equipment for the existing factory.

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

The current factory is represented by the input data in Table 3, as well as the output data from Trial run 1 in Table 4.

6.2.3. Simulation Experiments

In this case study, the number of input variables are simplified to only a few choices as shown in Table 4. 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 4), 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 4, 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 6 are calculated by running the simulation model. The model incorporates lifecycle assessment data from an European Union LCA database as described in [48].

Following are examples of conclusions arrived from looking at Table 4:

- 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 the above conclusions are not the only items to consider, however they provide additional information and support a better decision space than a normal non-discrete event simulation analysis. Such information related to sustainability can be very useful for decision making across the different phases.

Table 4 Simulation runs and their input data vs. output data changes

| | 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 4 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.

6.2.4. Discussions

The study results and output data are shown in Table 4. 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 4 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 4 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.

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.

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 to store and use sustainability and other related data for discrete event simulation is to utilize the Core Manufacturing Simulation Data Information (CMSD) [36] specification, which allows us to maintain neutral and accessible measures.

6. Conclusions and Future work

In this paper, a holistic approach to Sustainable Manufacturing Planning and Simulation was identified necessary and presented in an effort to bridge the gaps in the simulation tools to incorporate aspects pertaining to sustainability. To augment the approach and methodology we present a case where simulation can be utilized to generate design requirements or specifications for manufacturing systems in the early requirements or design planning stage or at the manufacturing planning stage.

The proposed SMPS approach can help industry achieve benefits such as:
- minimize energy use and improve productivity through improved engineering of product and process through planning and simulation
- promote environmentally responsible and economically competitive businesses
- implement a comprehensive monitoring and preventive maintenance program that takes into consideration energy usage through simulation
- deploying energy indicators into any plans that include asset acquisition, allocation, or replacement
- awareness of environmental impact when taking decisions / holistic system viewpoint for increased cause vs. effect understanding

Potential future work will include all or any of the following directions: a good simulation reference architecture, investigate models that support various stages of planning , dynamic scheduling with integrated manufacturing resources, sustainable material flow analysis, characterization of manufacturing cells for sustainable engineering planning and simulation, mapping of relevant data required at various levels of simulation, develop a core manufacturing ontology for simulation purposes, integration and interoperability of information at various levels, case studies, science based engineering simulation for characterizing different manufacturing processes in terms of the energy (source, use and efficiency, key controlling parameters), identify the scope and boundaries, e.g., enterprise level, shop floor level, etc, integrated or extended simulation with design optimization processes to simultaneously deal with factors such as manufacturability, cost, and environmental impact, new models and representations that support simulation for sustainable manufacturing planning and the integration of simulation applications with other relevant engineering/ manufacturing applications.

7. DISCLAIMER

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Appendix A:

Department of Commerce (DOC)
For the purposes of Commerce's Sustainable Manufacturing Initiative, sustainable manufacturing is defined as the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound [2].

National Council for Advanced Manufacturing (NACFAM)
Sustainable manufacturing includes the manufacturing of "sustainable" products and the sustainable manufacturing of all products. The former includes manufacturing of renewable energy, energy efficiency, green building, and other "green" & social equity-related products. NACFAM aims to address both of these topic areas and emphasize the sustainable manufacturing of all products taking into account the full sustainability life cycle issues related to the products manufactured [3].

NACFAM uses the definitions above and build off the concepts of the triple bottom line (developed by John Elkington [52]) and sustainable enterprise. The triple bottom line emphasizes financial profitability, environmental integrity, and social equity. This concept attempts to incorporate financial, environmental, and social capital into a comprehensive framework that can help companies analyze their current processes, innovate, and identify new sources of revenue and cost reduction.

Table 5 Relevant manufacturing data related standards

Information Model	Description
AP203	Application Protocol for Configuration Controlled Design [37]. AP203 defines the geometry, topology, and configuration management data of solid models for mechanical parts and assemblies. AP-203 Edition 2 is a new version of the AP-203 standard for exchanging 3D geometry between CAD systems. It includes Geometric Dimensions & Tolerances (GD&T) data. The new data has been designed to meet the requirements of design and manufacturing so the same model has also been incorporated into AP-238.
AP214	Core Data for Automotive Mechanical Design Processes [38]. AP214, designed for the automotive industry, defines the core data for the automotive mechanical design process, specifically the car body, power train, chassis, and the interior

	parts of a car. AP214 goes well beyond AP203, providing a far more comprehensive model for automotive applications and covering the lifecycle of a design from engineering through manufacturing. It also covers such design issues such as colors and layers, geometric dimensioning and tolerancing, and design intent.
AP219	Application Protocol for Dimensional inspection information exchange [39].
AP223	Application protocol for casting [40]. STEP AP 223 is part of a large standards effort to allow permanent storage and retrieval of technical and process information for castings.
AP224	Application Protocol for Mechanical Product Definition for Process Planning Using Machining Features [41]. AP224 is a vendor-independent digital product data specification that includes all information needed to manufacture and assemble a machined part. In addition to part geometry (dimension and tolerance) information, AP224 captures part features, material, surface finish and other notational information needed in manufacturing.
AP233	Application protocol for Systems Engineering and Design [42]. AP233 is an information model designed as a neutral data exchange capability for data created by Systems Engineering computer applications.
AP238 (ISO 14649)	Application Protocol for Computerized Numerical Controllers [43]. AP-238 is the official ISO STEP number for the STEP-NC standard. In AP-238 the information required to control a machine is linked to the information created by CAD and CAM systems to create a truly independent, fully documented CNC control file for the first time. ISO 14649 is the machining data model underlying AP-238. The authors of ISO 14649 assessed the state of the art in CNC, and developed an object-oriented data model based on the concepts of features and working steps that reflected today's high-performance machining needs. AP-238 takes this data model and brings it into the suite of STEP standards, so that CNCs can be fully integrated with CAD, CAM, CAPP and other CA- applications. AP-238 defines a new interface for existing systems.
AP240	Application Protocol For Process Plans For Machined Products [44, 45]. STEP AP240 can support macro process planning by connecting CAPP with CAM. This is because AP240 defines such a high-level process plan for a machined part, and contains data about manufacture of a single piece or assembly of single piece parts. It serves as an interface for capturing technical data out of the upstream application protocols, and issuing work instructions for the tasks required to manufacture a part and the information required to support NC programming of processes specified in the process plan.
CMSD	Data specification for efficient exchange of manufacturing life-cycle data in a simulation environment [46]. The objective leads to: foster the development and use of simulations in manufacturing operations, facilitate data exchange between simulation and other manufacturing software applications, enable and facilitate better testing and evaluation of manufacturing software, increase manufacturing application interoperability.
ISO14040	ISO 14040:2006 [47] describes the principles and framework for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements.
ISO14064	ISO 14064-1:2006 [48] specifies principles and requirements at the organization level for quantification and reporting of greenhouse gas (GHG) emissions and removals. It includes requirements for the design, development, management, reporting and verification of an organization's GHG inventory.
ISO14065	ISO 14065:2007 [49] specifies principles and requirements for bodies that undertake validation or verification of greenhouse gas (GHG) assertions. It is GHG programme neutral. If a GHG programme is applicable, the requirements of that GHG programme are additional to the requirements of ISO 14065:2007.
ISO50001	The future ISO 50001 [50] will establish a framework for industrial plants, commercial facilities or entire organizations to manage energy. Targeting broad applicability across

	national economic sectors, the standard could influence up to 60 % of the world's energy use.
RS274D (ISO6983)	RS274D is the data standard currently used to tell CNC systems how to make a part [51]. An RS274D file contains a list of instructions called G-codes. Each code tells the CNC machine where to move the cutting tool next. If the CNC executes all of the instructions correctly, then the part is made. Each code is very primitive and an RS27D file needs to contain hundreds of thousands of codes to make a part. The CNC is not given any information about what it is making or why the instructions have to be executed in the given order. Therefore, no optimizations can be made on the control. The RS274D standard is also limited in functionality, and CNC vendors have invariably extended it to include newer features in their controls such as spline interpolation. These "dialects" are not standardized, so programs written for one vendor's CNC are unlikely run on another vendor's CNC.
IGES	IGES is a standard for transferring drawing information between CAD systems and between customers and suppliers [52]. When a customer wants a job shop to make a part, it sends a description of the part as a drawing in an IGES file. The job shop then reads that IGES file into a Computer Aided Manufacturing (CAM) system and an operator uses it to generate the RS274D code necessary to make the part on a specific machine tool. It can take quite a long time for the operator to convert the drawing into RS274D codes and if anything changes the whole process has to start again. The people who developed IGES used the lessons learned to develop an international standard for the complete life cycle of a product and called it STEP. There will be no more versions of IGES after the current one.