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Title: An Information Modeling Framework and Desktop Application to Compose Unit Manufacturing Process Models for Sustainable Manufacturing Assessment

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The demand from consumers for more sustainable products, and the need to comply with government regulations motivates manufacturers to evaluate their operations for opportunities to reduce environmental impact and improve economic competitiveness. Manufacturers have actively improved the sustainability performance of their products through the use of sustainability assessment methods and tools. Recently however, manufacturers have struggled to maintain the necessary gains in energy and material efficiency due to the inadequacy of current, mature sustainability assessment methods and tools. This situation is compounded since new methods and tools continue to be developed for specialized applications, leading to inaccurate assessments in other domains. Overcoming these barriers requires standardized sustainability assessment methods and tools that are ready for use (plug-and-play) and contain accurate manufacturing process-level information. The research conducted herein posits that this barrier can be overcome through the advancement of information modeling and the automation of manufacturing system assessments. Thus, manufacturing process models would be composed to preserve information flows. Therefore, the work presented attempted three goals: 1) Assess the barriers to sustainable manufacturing through a review of the academic literature and roundtable meetings with industry; 2) Propose an information modeling framework to trace, capture, and control information flows within a composed manufacturing system for

sustainability assessment; and 3) Develop a desktop application implementing the framework to accelerate the sustainability assessment of composed manufacturing systems. Results from realizing the framework through an underpinning XML Schema and overlaying graphical user interface indicate that the presented approach would be useful in conducting sustainable manufacturing assessments. Future work should focus on improving the robustness of the information framework and the resulting XML Schema by incorporating validation content and structure for improved quality and composability of unit manufacturing process models.

An Information Modeling Framework and Desktop Application to Compose Unit Manufacturing Process Models for Sustainable Manufacturing Assessment

by
Matteo M. Smullin

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matteo M. Smullin, Author

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CONTRIBUTION OF AUTHORS

Chapter 2: Manuscript 1

Matteo Smullin performed a literature review to establish the state of the science in manufacturing process metrics, measurements, and modeling, and to present the findings of three industrial roundtable meetings conducted on the same topics. The primary direction of this work was led by Karl Haapala, along with Mahesh Mani, Kevin Lyons, KC Morris, Ian Garretson, and Harsha Malshe, who also assisted with hosting, notetaking, and helpful input, review and feedback.

Chapter 3: Manuscript 2

Matteo Smullin demonstrated the composing of two process models for sustainability performance assessment. Ian Garretson assisted with developing the process models. This work established the need for an informational modeling framework to assist such assessments. Mahesh Mani, KC Morris, Kevin Lyons, and Karl Haapala provided valuable input and direction of the work and helpful review and feedback.

Chapter 4: Manuscript 3

Matteo Smullin identified methods for capturing and modeling manufacturing process information based on past research. He and Ian Garretson developed conceptual system frameworks to visualize information flows within manufacturing systems. Smullin then developed the information modeling framework presented in the chapter with the assistance of Mahesh Mani and KC Morris. Mahesh Mani, KC Morris, Kevin Lyons, and Karl Haapala provided valuable input and direction of the work and helpful review and feedback.

Chapter 5: Manuscript 4

Matteo Smullin investigated automation of information modeling by developing a software application. The application aids developers in composing UMPs to create manufacturing system models. He reviewed software design with the intent of implementing a software application. The resulting application coded in C#, XAML, and MATLAB, was developed by Matteo Smullin with assistance from Zahra Iman. Karl Haapala provided overall project direction and valuable input and feedback on the work.

TABLE OF CONTENTS

TABLE OF CONTENTS(CONTINUED)

Page

TABLE OF CONTENTS(CONTINUED)

TABLE OF CONTENTS(CONTINUED)

TABLE OF CONTENTS(CONTINUED)

LIST OF FIGURES

LIST OF FIGURES(CONTINUED)

Page

LIST OF FIGURES(CONTINUED)

LIST OF TABLES

LIST OF APPENDICES

NOMENCLATURE

A_i	surface area of part i
AWG	average wage
B	Brinell hardness
C_i	cost of material or consumable i
Cop	operating cost
D	shot diameter
D_{nozzle}	nozzle length
DL_i	days lost by injury i
DL_j	days lost by illness j
Dt	distanced traveled
E	machine efficiency
ES	elasticity
EM_{ghg}	greenhouse gas emissions
ET	total energy consumed by process i
GWPCH4	methane global warming potential
GWPN2O	nitrous oxide global warming potential
ILL_j	number of unique illness j
INJ_i	number of unique injury i
L_i	length or thickness of i
$M_{capacity}$	capacity of freight truck
M_{fr}	total freight mass
P_{ac}	specific power of air compressor

$P_{ILL,i}$	probability of illness i occurring
$P_{INJ,j}$	probability of injury j occurring
P_{sp}	shot power
R_{CH4}	methane production rate
R_{CO2}	carbon dioxide production rate
$R_{haz,I}$	hazardous waste production rate of machine i
$R_{inc,I}$	waste to incineration production rate or machine i
$R_{land,I}$	waste to landfill production rate of machine i
R_u	utilization ratio
R_{N2O}	emissions rate of N2O
W_i	wage of laborer i
W_{total}	total waste produced
V_a	volume of air consumed
V_{fu}	volume of fuel consumed
V_p	volume of paint consumed
Y	fill factor
YS	yield strength
A	solid angle
A	rake angle
B	friction angle
sa_p	surface area coated
c_E	energy cost
a	indent radius

c	coverage
d	indent diameter
d_t	paint layer thickness
e	coefficient of restitution
$h_{observed}$	observed dent depth
h_p	predicted dent depth
k	coverage factor
m	mass flow rate
m_i	mass of object or consumable i
m_{sp}	shot consumption
n_l	number of paint layers
p	pressure
p_{cov}	shot coverage percentage
q_i	airflow rate for process i
r_{fc}	fuel consumption rate
r_{sf}	shot flow rate
s_d	standoff distance
t_b	shot batch time
t_i	process time task i
t_L	labor time
$t_{L,i}$	time worked of laborer i
v	volume of indent
v_a	average velocity
v_{sp}	shot velocity

Z	Coverage factor
Z_t	Time to achieve % coverage
ρ_i	density of substance i
θ_R	angle of the cutting tool within one revolution
μ_0	magnetic constant
μ_{oven}	efficiency of oven
ρ_i	density of substance i
ρ_Ω	electrical resistance of material
σ_{UTS}	ultimate tensile strength of the steel
σ_{YS}	yield strength
σ_Ω	electrical permissively of material
Φ	shear angle
α	divergence angle

CHAPTER 1: INTRODUCTION

Motivation

In the United States, manufacturing consumes 31% of all energy produced [1], consumes 25% of all potable water [2], and produces 21% of all greenhouse gas (GHG) emissions [3]. Since 1990, industrial energy consumption and GHG emissions have plateaued as manufacturing has become more efficient [1]. However, energy use and GHG emissions have continued to grow for other sectors of the economy. To reverse the effects of increasing energy use and related emissions (e.g., fossil fuel extraction and global climate change), manufacturing industry must continue to innovate to reduce materials and energy use. Achieving a sustainable future requires industry to pursue sustainable manufacturing, where sustainable manufacturing is defined as the manufacture of products where "the needs of the present are met without compromising the ability of future generations to meet their own needs" [4]. Sustainable manufacturing comes about by addressing the product or process comprehensively, e.g., conservation of energy and natural resources, safety for employees and surrounding communities, and economic viability [5]–[8].

To achieve this goal of sustainable manufacturing, researchers have focused in part on characterizing the sustainability performance of unit manufacturing processes (UMPs), where one process can consist of one or more machines [9]. Under the umbrella of UMP research, researchers have investigated the effect of tool and machine factors on sustainability performance, while others have investigated UMP and UMP-based manufacturing system sustainability assessment [10]. Each research focus builds upon the other, with improved understanding of process and machine impacts, process and system models become more accurate, and with more accurate models, sustainable performance assessments uncover additional opportunities to advance sustainable manufacturing.

Creation of more informative, predictive, and accurate process and system models requires improvements to current methods and tools, and the development of new methods or tools for previously unidentified research deficits. While current, older methods and tools for sustainable manufacturing assessment have seen widespread adoption, their capabilities have been readily exhausted and more recent methods and tools have not seen adoption among manufacturers at a rate necessary for meaningful change [11]–[14] . Further, existing methods and tools (e.g., life cycle assessment) are unable to aggregate process level sustainability impacts to systems level assessments. Rectifying this situation requires elucidating the information transformations occurring when more than one manufacturing process is linked to others to form a manufacturing system. The common link between processes is the workpiece, thus, the workpiece acts as a carrier of information transferred from one process to the next. Information model development requires understanding the physical transformations to the workpiece and the resulting information changes as it passes from a process to a workpiece and, subsequently, from process to process via the workpiece.

Background

Since its genesis in the Brundtland commission report of 1987 [4], sustainability has seen many methods and tools either adapted from other fields or built from scratch to identify opportunities for sustainable performance improvement. The most successful method to arise from early research was life cycle assessment (LCA). LCA holistically evaluates the environmental impacts of a product from cradle (creation) to grave (disposal or recycle). The method tallies the material and energy inventories for making a product at each stage of the lifecycle, including material extraction, processing, manufacturing, use, and disposal. As a first foray into manufacturing assessment, LCA uncovered many opportunities for improvement, from reducing packaging waste, to better recycling, to more sustainable transport. However, LCA is limited by its inability to account for process level impacts on the environmental performance of a product [11]and other limitations regarding the use of LCA [12], [13], [15]. Firstly, it is inaccurate. LCA does not investigate any one phase in great detail. Rather, LCA assesses the happenings at each phase with broad strokes. Further, using the LCA method is time intensive, and exhibits steep learning curves. More recently work has progressed towards answering the limitations of LCA, with particular emphasis on the manufacturing phase, since this phase accounts for a large portion of the environmental impacts of a product over its life cycle.

To address the manufacturing phase, researchers have investigated the building blocks of manufacturing process flows: unit manufacturing processes (UMPs). A UMP constitutes one or more machines with one or more tool sets all sharing a common value adding purpose[9]. Over 80 years of academic research have been invested into characterizing UMPs [16], thus the conceptual image of a UMP has been well formulated (Figure 1) starting with Kim et al. [17] and terminating more recently with attention of the ASTM WK35705 [18] work group to developing a standard for sustainability characterization of a manufacturing process.

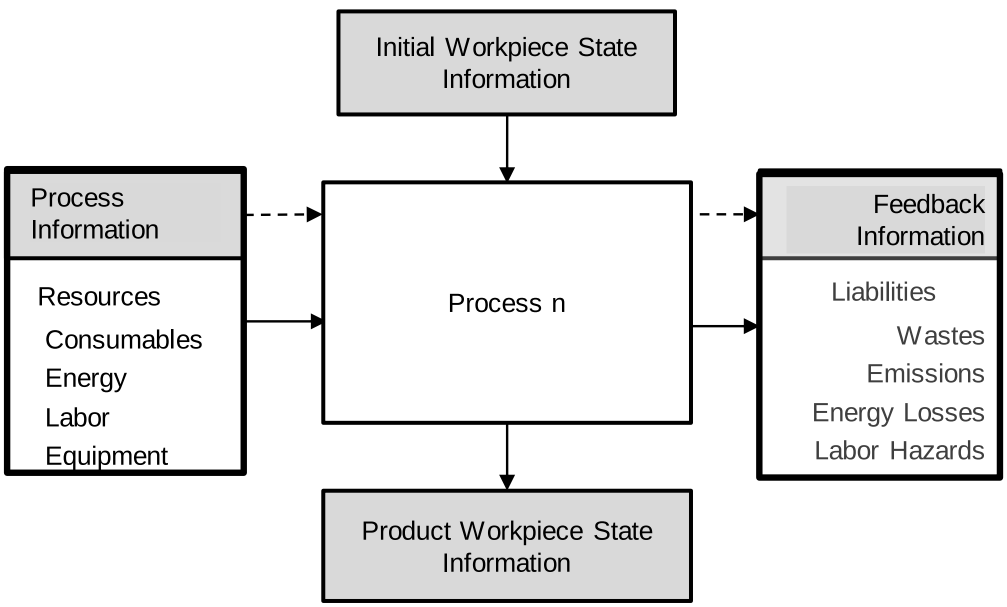

Figure 1: A conceptual illustration of a unit manufacturing process with emphasis on the underused information (shaded grey).

A UMP can be characterized using one of several taxonomies [19]–[21], with no one taxonomy being broadly preferred for industry or academic use. Within this body of work, Todd et al. [20] is followed to maintain consistency with previous work by Garretson [22] in this domain. Todd's taxonomy proposes that a UMP is labeled by its activity. A UMP that removes workpiece material is labeled as such (*material removal*), while one that modifies the surface of a workpiece is labeled accordingly (*surface modification*).

While much recent effort has focused on modeling of UMPs, less work has been reported on methods to link these models to produce composed manufacturing systems. As such, process flow models tend to be constructed in a manual fashion where each UMP is independent and uninfluenced by the actions of neighboring UMPS. This lack of interconnection results in little preservation of information transfer between UMP models. In large part this situation where UMPs are left independent and not linked stems from the acknowledgement that modeling UMPs and systems composed of UMPs require different approaches. Duflou et al. [23], for example, suggested optimizing process parameter settings at the device/unit process level, and using simulation and optimization for production planning at the multiple machine system level. While methods are widely reported for optimizing process parameters and improving process level sustainability, little is available to do the same for production planning, in particular by preserving connections between UMPs within a manufacturing system.

A manufacturing system, also called a manufacturing process flow (MPF) [22], consists of more than one UMP chained together to deliver a finished final product to an end customer (Figure 2). Zhao et al. [24] claimed this form of process planning has a large impact on cost and environmental effects in product manufacturing as it enables evaluating alternative manufacturing systems. However, little research has focused on manufacturing systems, with the result that most manufacturing systems are created manually and in an *ad hoc* manner. All manufacturing systems rely on characterization not only of the constituent UMPs, but also of the linkages between them. The act of linking UMP models together is known as *composability* and requires that information be captured and labeled properly within each UMP and the workpiece transiting the system. This allows the individual UMP models to “talk” to one another and become composed. Davis et al. [25] made the astute judgement that in order to be meaningful, manufacturing system models requires connecting UMP models such that decisions made in one UMP are actively reflected in the other. This effort is inhibited by the observation that UMP composability is constrained by a number of fixed constraints. In addition to the computational complexity of quantifying numerous model outputs for alternative scenarios or optimization, the diversity of UMPs requires manual modeling efforts. While the complexity and diversity of UMP models is innate, the method for modeling UMPs and their linkages can be standardized such that information is always labeled and structured in a uniform manner. To do this requires information models and a standardized framework controlling the identification of information flows, and their appropriate structuring and labeling.

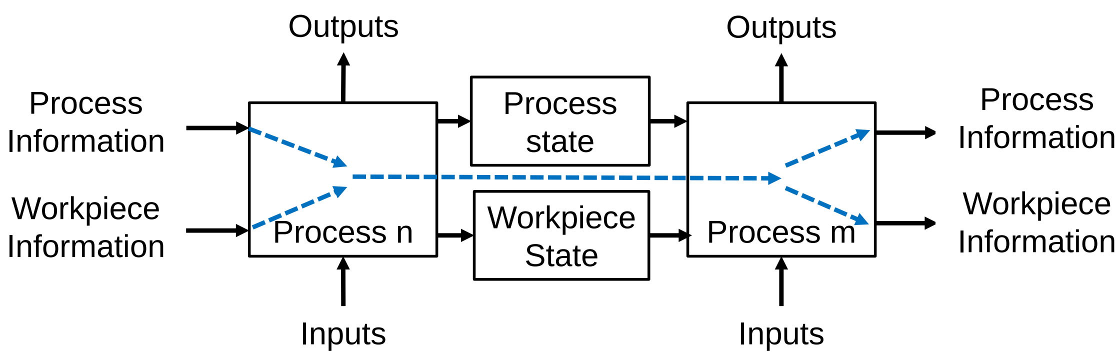

Figure 2: A conceptual view of a composed manufacturing system where two or more unit manufacturing processes are linked to preserve information flow between

Information models define different concepts, relationships, constraints, rules, and operations to structure data semantics within a given domain [26]. In this way, a UMP model classified as a material removal operation will have the same structured data setup as a surface finish operation. Many information models have been created and presented in the literature for elements of manufacturing. However, none so far attempt to cover UMP modeling and composability. As a result of this lack of an information model for UMP composability, the characterization of UMPs and manufacturing systems has become *ad hoc*, with different approaches advocating unique methods that pull from various data sources, label information differently, and structure information in incompatible manners.

Research Objectives

The objective of this thesis research is to understand the structure of manufacturing processes and systems to enable reliable, semi-automated modeling and composing of unit manufacturing processes toward more accurate sustainable manufacturing system assessment. From this objective the following questions are derived:

Question 1: What is the state of industry practice and academic research on the topics of manufacturing metrics, measurement, and modeling for sustainability assessment?

Question 2: What types of manufacturing information is required to compose unit manufacturing processes into manufacturing process flows?

Question 3: How must information be structured and labeled to support sustainable assessment of composed manufacturing systems?

Research Tasks

To fulfill the research objectives, the following research tasks were undertaken:

Task 1: Host a series of industry roundtable meetings to gather input on the state of sustainable manufacturing within their operations, with emphasis on manufacturing metrics and process modeling. Evaluate industry input to identify key barriers and recommendations to and for improving sustainable manufacturing operations.

Task 2: Investigate the feasibility of composing UMPs to produce more accurate manufacturing system models through literature review, manufacturing theory, and mathematical modeling.

Task 3: Develop and demonstrate a framework for information modeling to facilitate the composing of UMPs for sustainable systems assessment. Develop the framework to model the relation between sustainable performance indicators and UMP models, elucidate the information flows between UMPs, and determine a mechanism to structure and label information to aid manufacturing systems assessment. Demonstrate the framework by developing a desktop application to semi-automate the composing of UMPs and producing sustainable assessments.

Thesis Outline

This research conducted as a part of this thesis suggests answers to these questions and produces results for each task. This thesis is formatted following the manuscript format. Each chapter presents a manuscript detailing research towards one or more questions and tasks which were detailed in Chapter 1.

Chapter 2 presents a literature review coupled with evaluation of industry input gleaned from the roundtable meetings (submitted to the *Journal of Cleaner Production*). It presents a narrative and systematic literature review of manufacturing metrics and measurement, and manufacturing process modeling in the sustainable manufacturing domain. This literature review is presented in contrast to the evaluated input of the roundtable meetings. The result is a clear picture of the key barriers and recommendations to overcome the divide between academic research and industry practice.

Chapter 3 presents a conference article published in the *Proceedings of the ASME 2016 Manufacturing Science and Engineering Conference*, and presents proof of concept evidence to support composability by characterizing UMP models and modeling the composition of the UMP models. The methodology is demonstrated on a high performance automotive part to illustrate composability's ability to improve modeling accuracy.

Chapter 4 is an article to be submitted to *Journal of Advanced Engineering Informatics*, and creates an information modeling framework to capture UMP information and workpiece information. The framework's potential is demonstrated for two UMPs and directions are given for future work in this area.

Chapter 5 presents a conference article submitted for the *Proceedings of the ASME 2017 Manufacturing Science and Engineering Conference,* and presents the implementation of the information modeling framework within a software application. The work performed earlier in Chapters 3 and 4 is incorporated to produce a comparison of two alternative UMP-based manufacturing systems, each of which is capable of making a high performance automotive part as first demonstrated in Chapter 2.

Chapter 6 summarizes the research performed, presents the research findings, conclusions, and contributions, and identifies opportunities for future work.

CHAPTER TWO: USING INDUSTRY ROUNDTABLES AND LITERATURE REVIEW TO IDENTIFY CHALLENGES TO SUSTAINABLE MANUFACTURING STANDARDS DEVELOPMENT AND ADOPTION

By
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CHAPTER 2: USING INDUSTRY ROUNDTABLES AND LITERATURE REVIEW TO IDENTIFY CHALLENGES TO SUSTAINABLE MANUFACTURING STANDARDS DEVELOPMENT AND ADOPTION

Abstract

The bottom-up demand from consumers for more sustainable products, and the top-down need to comply with government regulations motivates manufacturers to improve the sustainability of their products through the use of sustainable assessment. Recently, however, manufacturers are struggling to maintain the necessary gains in energy and material efficiency due to the inaccuracies of current assessment instruments and, often, an inability to identify meaningful sustainability-related improvement opportunities due to a lack of resources. Overcoming this barrier requires standardized, publically available instruments that use and contain accurate manufacturing process-level information. To examine this view, this study contrasts the perspectives of industry and academic research on the topics of sustainable manufacturing metrics and indicators, measurement tools and methods, and process modeling to determine the challenges that exist in enacting academic theory to practice. Narrative and systematic literature reviews were performed using qualitative and bibliometric analysis to establish the academic research perspective. Also, three industry roundtable meetings were hosted, where focus group and nominal group techniques were used to establish the industry perspective. A survey of the roundtable participants was conducted to confirm a consensus. The results indicate that academic research is disparate, with no agreed upon best practices for improving assessment accuracy. Despite recent advances, industry continues to see sustainability as ill-fitting with core business practices and has yet to be persuaded otherwise, largely due to a lack of instruments capable of evaluating systemic improvement opportunities. These findings indicate the need for standards to unify academic research and industry practice and to improve assessment accuracy in order to enable industry to effectively conduct sustainability assessments and perform sustainability decision making.

Keywords

Literature Review, UMP Characterization, Focus Group, Survey, NGT, Measurement Science, Standards

Introduction

Since rising to the fore in the Brundtland report [4], the concept of sustainability has continued to mature as consumers have become more conscious of the impacts of their purchasing behavior and habits and as companies have pursued environmental and social responsibility. Consumer perception is notably challenging to define, thus industry's focus often has been to evaluate the energy and material consumption of products during the manufacturing phase to improve cost efficiency and reduce energy-related environmental impacts (e.g., greenhouse gas emissions). Social issues are often addressed by supply chain changes, health and safety programs, and community service and involvement. Companies have used a multitude of methodologies and indices to assess their sustainability impacts [27], with each methodology and index hosting its own set of unique or regionalized metrics. However, very few are both accurate and simple to use. Similarly, some tools for system level sustainability analysis have seen widespread adoption (e.g., life cycle assessment [LCA] tools) with other tools coming online in recent years for process level analysis (e.g., unit process life cycle assessment [UPLCI]). The breadth of available tools, the expertise required, and the lack of comparability has made industry reticent to continue investing in unproven sustainable assessment instruments without a clear return on investment.

Standardizing sustainable techniques assessment instruments offers a promising alternative to the *status quo.* By standardizing a common set of agreed upon metrics, indicators, and process modeling techniques, companies could be given reason to adopt new tools and methods capable of systematically improving the accuracy of their process and system level sustainability assessments. Thus, the goal of this work is to compile information about current industry practices, perceived barriers, and future opportunities for improved sustainability assessment. In addition, a review of academic literature was conducted to compile recent research toward improving sustainable manufacturing assessment.

Standardization of sustainable manufacturing assessment from theory to practice requires first understanding the current state of the art as it relates to three overarching areas: (1) manufacturing metrics and indicators (2) measurement methods and tools, and (3) manufacturing process modeling. Further, it is important to take this understanding of the state of the art and contrast it with industry perspectives to clarify potential barriers and solutions to standardization. The work to this end is reported below. Section 2 presents the approach followed to conduct narrative and systematic literature reviews on sustainable manufacturing metrics and measurements and manufacturing process modeling. Section 3 presents the approach taken in hosting the roundtables and qualitatively assessing the collected data. Sections 4 and 5 present the results of the narrative and systematic literature reviews, respectively. Section 6 presents the findings from the industry roundtable meetings. Section 7 presents barriers and gaps identified by contrasting the industry and literature perspectives, and, Section 8 concludes by identifying the common trends from the literature and the roundtables that should be addressed in future work.

Background

Sustainable manufacturing is defined as the creation of manufactured products using processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound [28]. To that end, researchers have created methods to assess the environmental, social, and economic impacts of manufactured products or processes through myriad indicators and metrics [29]–[31].

Over the past two decades, studies have repeatedly emphasized a lack of accurate tools and methods to support sustainable manufacturing. A seminal global study on environmentally benign manufacturing [32] supported the consensus that better assessment tools and more accurate data is needed. Bunse et al. [33] reported on the implementation gap between academic theory and industrial practice. Through interviews they affirmed their initial hypothesis that standardized tools and methods could speed adoption of sustainable practices. Bhanot et al. [34] published the results of a survey concluding that one of the main barriers to sustainable manufacturing is the lack of standards. This same conclusion was expressed by Rachuri et al. [35] nearly four years earlier following a workshop on sustainable manufacturing best practices with experts from industry, academia, and government. These studies have all echoed the need to focus on developing process-level understanding to characterize manufacturing sustainability performance.

Process level sustainability analysis revolves around the characterization of one or many unit manufacturing processes (UMPs). A UMP is considered the smallest element, or step [36], [37], in manufacturing that adds value to a workpiece through an imparted physical, chemical, or geometric transformation of inputs to outputs [6]. Overcash and Twomey [38] noted that UMPs are often interchangeable for the production of a given part. The choice in selection oftentimes relies on the tacit experience of engineers who evaluate the required inputs to achieve a desired workpiece state (e.g., surface finish or workpiece hardness). Further, UMPs are not to be confined to a single machine or worker action, as they can span multiple machines and workers so long as further dissecting the process reveals no more underlying transformations [22].

Characterizing a UMP requires first selecting an initial set of suitable indicators and metrics. A metric is defined as a standard measure of a single parameter of a system. A metric must be measurable, relevant, understandable, reliable, usable, data accessible, timely and long term oriented [39]. Indicators and metrics relate sustainability performance areas to each other and to the process in question. Each performance area can have one or more indicators. In turn, an indicator can be described by one or more metrics. Indicators provide a context to measure, analyze, and score sustainability aspects of manufacturing processes. What defines an indicator is still a topic of much discussion amongst the literature. The clear definition comes from Veleva and Ellenbecker [8] who summarily settle on defining an indicator as a variable and thus “an operational representation of attribute (quality, characteristic, property) of a system" [40]. Indicators can be defined internally, or selected from various indicator repositories. Evaluation metrics associate the process (es) to be evaluated with the identified indicator (ASTM E2986, 2015).

Once metrics and indicators are selected, a UMP model can be developed from mechanistic relationships or empirical measurement and observation. UMP models can track the transformation of material and energy inputs to outputs while reporting out variations in the process [41]. Thus, a UMP model can be used to explore process and material interactions and to quantify sustainability metrics, which would provide opportunities for improvement to the process and/or system in product manufacturing [42]. A UMP model incorporates process and workpiece analytics in a standardized manner [18]. This allows reusability of the model in sustainable manufacturing evaluations. A process model links the internal transformation of inputs to outputs to the evaluation metrics selected for final performance evaluation [36]. Measurement science is the development of performance metrics, measurement and testing methods, predictive modeling and simulation tools, knowledge modeling, protocols, technical data, and reference materials and artifacts [43]. Measurement science is the umbrella under which UMP characterization resides. In this umbrella, UMP characterization acts to establish the foundation where data is labeled to create information, and that information becomes knowledge through tool and method development.

In order to advance measurement science within sustainable manufacturing a series of literature reviews and industry focus groups were undertaken as discussed in the next section.

Research Methods

The methods utilized to compare and contrast the academic and industry perspectives toward sustainable manufacturing assessment are summarized in Figure 3 and a description of the narrative literature review and complementary systematic literature review methods are presented in the next sections. For each literature review, publications were quantitatively and qualitatively reviewed from January 1, 1994 to June 30, 2016. Industry roundtable meetings consisting of focus group and nominal group techniques sessions were hosted to gather industry input and are presented after reviewing the literature review methods.

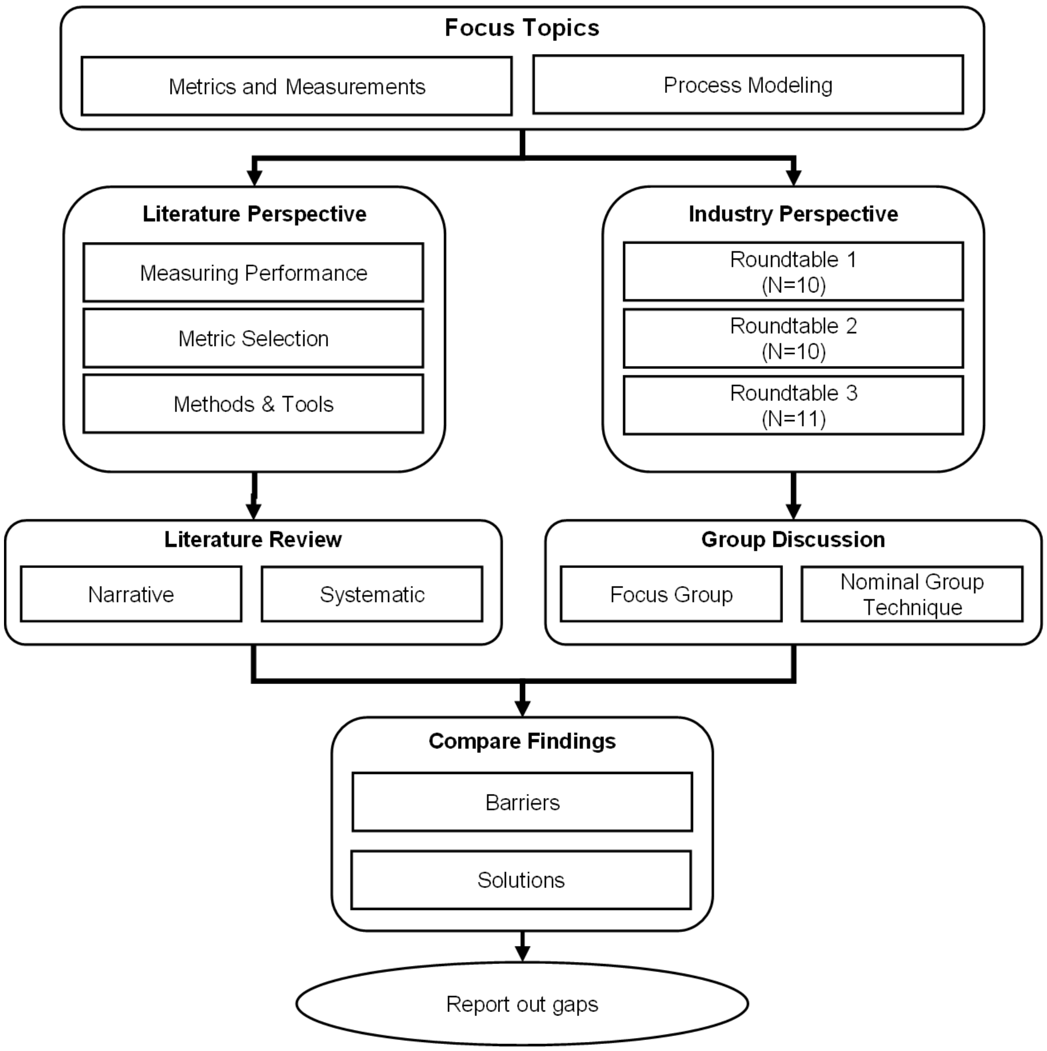

Figure 3: Conceptual outline of the research method presented herein

Literature Review Approach

A total of 110 publications were reviewed in this study for the time period of January 1, 1994 to June 30, 2016. The selected start date (1994) reflects the first study found where sustainability research was extended to manufacturing process and product modeling. The publications within this time period were first reviewed using the narrative literature review method. Following the narrative review, a systematic review was conducted using the same timeframe and topic areas. These methods are described in the sections below.

Narrative Literature Review Method

The narrative method is the classic approach to conducting literature reviews. It identifies the research purpose, clarifies the key concepts, defines the boundaries of analysis, and highlights research pushing to advance the boundaries of the field. Narrative reviews excel at identifying the underlying research trends and the deficits still to be addressed for a given research area [44], [45]. The narrative review reported chronologically herein presents the research on the two aforementioned topics: metrics and measurements, and process modeling, as well as work to develop supporting tools. Further, specific focus is applied toward highlighting the challenges of enacting sustainable manufacturing theory to standardized practice, as previously identified by researchers and practitioners.

Previous literature reviews have identified the breadth of sustainable metrics and indicators [31], the diversity of process modeling approaches [46], and the myriad sustainable assessment tools available [47], while others have reviewed the research into sustainable manufacturing [48] However, there has been no studies of late concisely presenting the relevant work towards standardizing sustainable manufacturing assessments. This research attempts to fill this gap through broad, shallow review of the state of the art in sustainable manufacturing according to this need for standard measurement science instruments.

Systematic Literature Review Method

The systematic literature review is a quantitative analysis method that has been developed for classifying research efforts. Originally developed in the medical field, the method has recently seen broader adoption in other fields. The primary benefit of the SR method is the ability to reduce the inherent author bias in presenting narrative reviews. The bias stems from the natural tendency of authors to select publications for review supportive of the author's viewpoint [49]. Through the use of publication data, citation data, and keyword analysis, SRs act as a quantitative counterbalance to narrative reviews. Furthermore, the analysis of these datasets provides key characteristics of past research and strategies for future work. For this reason, a systematic literature review is performed complementary to a narrative literature review to ideally present an unbiased review of publications and citations in standardizing sustainable manufacturing assessments. Due to the youthfulness of the SR method, there is no large corpus of SRs reported within sustainability literature, especially with an emphasis on sustainable manufacturing. SRs have been reported for sustainable supply chains [50], business operations [51], [52], and lean manufacturing [53]. However, no SR studies were found in the area of sustainable manufacturing, nor in the context of standardizing sustainable manufacturing assessments. Thus, this study applies common SR analysis methods (e.g., normalized bibliometric coupling) [54] to publication and citation data and keywords to objectively address this gap in the research literature. The results provide a novel classification of available studies.

Roundtable Approach

The industry perspective was gathered by hosting three roundtable meetings with 8-12 industry participants. Each roundtable meeting was organized into three dialogue sessions lasting approximately two hours each. The term "roundtable" encompasses both the focus group and NGT dialogue sessions. Questions were designed to foster discussion in each area of interest, while allowing time for note takers to document relevant information. The roundtables were hosted from June 2015 to March 2016. The roundtables were distributed geographically to gather a diverse set of industry participants and information, since similar companies tend to cluster to achieve greater competitiveness [55]. Represented companies spanned a range of industries and sizes, from small high tech startups to well established, large manufacturing companies.

The intent of the first dialogue session of each roundtable was to foster discussion about performance indicators, processes, process flow and plant/facility performance, and the communication of metrics. While the second dialogue was intended to foster discussion about capturing and describing sustainability information at the process level to support system level decision making. Topics included manufacturing process modeling and benefits of process characterization. The third dialogue centered on identifying barriers to four sustainability topics and generating solutions to overcoming these barriers.

To determine how the dialogue sessions would be conducted, the authors investigated four well known methods for soliciting opinions from subject matter experts: the Delphi, brainstorming, nominal group, and focus group techniques [56]–[58]. NGT is an alternative approach to group discussions designed to minimize personal conflict and maximize the relevancy of the group consensus. The implicit theory for NGT and other group idea creation methods is that groups generate better ideas than individuals [58]. The next sections present focus group and NGT in greater detail.

Focus Groups

From the investigated methods, the authors selected the focus group method for its strength in extracting the range and diversity of participant's agreements and disagreements [57]. Focus groups are a research technique to collect data based on personal experience and opinion from a set of participants presented with a question from a researcher. Krueger and Casey [59] established some of the first guidelines for applying the focus group technique. The guidelines recommend that a focus group be conducted in three phases: conceptualization, interview, and analysis. During conceptualization, ten participants are selected who are most qualified to give reasoned opinions on the desired subjects. Questions are formed that are designed to elicit specifics, but remain open ended. In this regard, 8-12 participants were identified for each roundtable. A set of five key questions were formulated and discussed by the research team to ensure they remained open-ended, specific, and logically sequenced. In the interview phase, the moderator, who is assumed to be knowledgeable on the discussion topics, begins the discussion with a welcome, overview, and ground rules before asking the first question. Time is allocated to allow participants to socialize prior to beginning the discussion. In keeping with this guideline the authors designed the roundtables to allow informal greetings over a continental breakfast before formally welcoming and introducing the participants to the dialogue topics. Furthermore, focus groups are designed such that each participant individually responds to the moderator's question with their own perspective of the situation. To ensure this, the roundtable moderator walked within the perimeter of the open circle of participants and questioned each participant in round-robin style on each topic. When each participant had voiced their answer, the floor was opened for group discussion. In the final analysis phase, the field notes collected by the researchers were collated and compared. Raw data was qualitatively described and interpreted and reported out to participants and the research team observers to achieve consensus on the interpreted findings. The resulting findings are described later in the Results Section. The key ideas from each roundtable are reported. Where available, specifics are given to substantiate the claims in the form of quotes or mentioned tools and methods.

Nominal Group Technique

NGT is a three phase process [60]. In the first phase, participants are asked to arrive at the meeting, or roundtable, with foreknowledge of the topics. To ensure all participants arrived equally apprised of the topics to be discussed, the organizers distributed a background handout to participants prior to the roundtable meeting. The second step in the NGT process is for a moderator to individually ask participants for their responses to the questions asked. In this way, no individual is overshadowed by the personality of another, and those disposed to silence are encouraged to participate. Further, this approach minimizes the interaction within participants during dialogue sessions to better maintain focus on generating individual responses to the questions of interest. The third phase of the NGT involves the participants iteratively ranking all the generated answers to arrive at a final consensus of what is the best answer(s). This final phase of the process was modified by the authors. Due to time constraints and the scope of the research, the responses were compiled and organized by the organizers after the roundtable. The compiled responses were distributed to the participants for comments and approval.

Narrative Literature Review

The literature review conducted in this section identifies the need for standards for sustainable manufacturing assessment from the perspective of the academic and industrial research community. Challenges in sustainable manufacturing that could readily be addressed by standards development are identified by focusing on metrics and indicators, measurement methods and tools, and process modeling.

Metrics and Indicators

This section first reviews the conceptual approaches commonly taken to develop metrics and indicators for sustainable manufacturing. Next, the common characteristics of indicators and metrics are reviewed and, specifically, whether they address all three aspects of sustainability. Below, the level of development (i.e., product, process, factory, and system) for each stage of sustainable manufacturing are discussed. Finally, a review of methods for aggregating metrics and indicators is presented.

Some of the first indicators created to assess sustainability arose within the LCA movement [61], [62], and were used to evaluate company environmental performance [63]. Sarkis [64] was among the first to investigate the applicability of environmental indicators to the lower levels of the manufacturing phase of LCA. Other indicators were developed independent of LCA to address aspects of sustainability in addition to environmental impacts [8]. A common conceptual approach to incorporate sustainability performance into manufacturing has been the modification of existing business methods. This has largely involved the modification of lean manufacturing principles and techniques; under the terms Green Manufacturing and Lean and Green, for example, studies have investigated means for adapting in-use lean tools to assess sustainability. Faulkner and Badurdeen [65] proposed adapting Value Stream Maps to incorporate environmental and social metrics along with in-use economic metrics (e.g., throughput, cycle time, and quality). The commonly held perception among lean practitioners is that the focus on waste reduction makes lean a natural driver for sustainable change [66]–[69]. This belief is not without its detractors, who note that lean can be at odds with sustainable principles [70].

LCA and lean adaptation aside, the development of industrially-relevant sustainability indicators has remained largely static. Common indicators continue to be related to materials, energy, and wastes [71]. These are tactile and easily measurable at factory and operational-levels. Social indicators are regularly excluded, a trend that is at odds with the stated goal of sustainability to holistically address economic, environmental, and social issues. This trend has begun to shift recently; for example Shuaib et al. [72] addressed this concern by including the social aspect in a metrics-based index to evaluate the life cycle impact of manufactured products. Further, the United Nations developed a social sustainability index that acted to quicken research in the field [73]. Another recent shift has been to extend indicators and metric-based assessment methods to evaluate factory, line, and unit process-level impacts. Linke et al. [74] noted a scarcity of process-level metrics, and developed process-level metrics for use in grinding operations. At the factory-level, [75] accounted for factory overhead in their process models, noting that factory elements such as HVAC had conspicuously been absent from decision making tools. The reason sustainable manufacturing analysis has remained at the system level (e.g., LCA) as opposed to the process level is largely uncertain, though Terkaj et al. [76] noted a key barrier may be a lack of available standards. While standardizing a core set of encompassing metrics for each level of manufacturing remains a challenge, a second challenge arises when attempting to aggregate these metrics across organizational levels.

Aggregation, such as aggregating process level metrics into system and operational level sustainability assessments [77], is a challenge that few have attempted to address. Lu et al. [78] noted one of the challenges is that process and product metrics can originate from the same performance indicator, but may differ in their goals and quantification approaches. One avenue of addressing aggregation challenges, by using the same indicator, is stymied by the need to develop different measurement methods. Thus, metrics and the underlying data structure and sharing method must be standardized. In the absence of standards, Feng et al. [79] proposed using efficiency ratio metrics. In this manner, the idealized consumption of varying process or product designs can be considered as proportions to actual consumption levels. This allows reusing the same metric, since it is unit less across levels. Linke et al. [80] noted that energy and material efficiency indicators are not applicable to all manufacturing processes. For example, they reasoned that material removal rate (MRR), despite its popular use in waste reduction methods, is less useful than quality or change in performance metrics for assessing surface finishing operations. The need to develop metrics unique to process and manufacturing system levels has led to a profusion of available metrics. Moreover, as research has investigated various angles of sustainability, more indicators have been developed to increase assessment accuracy and produce a more holistic assessment.

Despite the continued existence of gaps in indicator and metric coverage, a parallel profusion of indicators and their associated metrics has occurred within well researched areas of sustainable manufacturing. In effect, while areas of UMP and system characterization have been overlooked, other more mature areas of sustainable manufacturing have experience over development. This profusion over the past two decades has not gone unnoticed within the sustainable manufacturing field. Singh et al. [27] reviewed a number of sustainability assessment methodologies covering problem definition, metric selection, and metric quantification. Joung et al. [31] reviewed the range of available indicators, and classified them into five categories. As mentioned above, even with the large range of available indicators, many lack related measurable metrics, in particular with relation to the social aspect. Thus, despite the advancements in assuring that social sustainability is addressed, a logical gap in sustainable performance metrics yet remains. Baumgartner and Ebner [81] attributed this gap to an inability to accurately assign a quantitative metric to a number of qualitative indicators. Hassini et al. [82] in reviewing sustainable supply chains, gave credence to the notion iterated above that standards are needed to provide companies with guidance for enterprise level starter indicators that can be specialized over time as company experience improves.

Measurement Methods and Tools

This section presents a review of the measurement methods and tools proposed by researchers to assess sustainability at the product, process, factory, and system level. This section begins by presenting the diversity of methods available in research. Methods are reviewed on account of their decision making approach, mathematical underpinnings, and outcome goals. Following the methods review is a similar recounting of tools proposed in the literature. Overlap is to be expected, as many methods are intended for use within software or physical tools and are presented in research in a likewise manner. Finally presented is a review of the challenges faced in developing holistic tools and assessment methods capable of aggregating results.

When a set of indicators and metrics is selected by a company or engineer, the next step to assessing sustainability is to assign weights to the metrics and indicators. Ibáñez-Forés et al., [83] reviewed the qualitative and quantitative methods proposed to calculate indicators and weight criteria in sustainable performance assessments, and reported no mathematical method prevails. One method proposed to solve conflicts between economic, environmental, and social performance metrics has been multi criteria decision making (MCDM). Zhang and Haapala (2012) reported an MCDM approach to evaluate the influences of manufacturing process and system criteria on operational decision making. They demonstrated the approach to assess the sustainability of a work cells, and incorporated unit process metrics into operational decision making. Other quantitative methods employed in the literature for ranking and preference selection have spanned fuzzy logic, analytical hierarchy process (AHP), and quality function deployment (QFD) approaches [84]. Fuzzy logic methods have seen recent implementation in decision aids for small and medium size enterprises (SMEs) to rank metric importance as low, medium, or high [85] or to assess social sustainability performance [86]. AHP has seen extensive use. AHP is a method to rationalize decision making by assigning weights to criteria used to evaluated a goal, as such they lend themselves well to sustainability methods. Jiang et al. [87] utilized AHP to assign weights encoded in their manufacturing environmental performance evaluation (MEPE) tool. The goal of these quantitative methods is to ease the burden in selecting appropriate metrics and ensuring the results are relevant. Research has also investigated whether qualitative or hybrid approaches would be more suitable for metric selection and weighting. Despeisse et al. [88] presented a qualitative, five-step methodology based on qualitative self-assessment of operations to aid SME decision makers in selecting the appropriate quantitative tool from the literature. Bilge et al. [89] developed a hybrid approach to rapidly convert qualitative stakeholder requirements into indicators using assigned values in an approach similar to AHP.

Much like research into the development of measurement methods, tool development has been extensive. Carnahan and Thurston [90] presented one of the first tools to sustainably design for manufacturing.. The mathematical approach involved statistical process control and multi objective/attribute design optimization to quantify air pollution and scrap rates. Sarkis et al. [91] applied AHP and discrete element analysis (DEA) within a framework to review the environmental soundness of proposed manufacturing plans. Other common mathematical approaches seen in tool development mirror those found in method development – often as means to demonstrate the reported approach. Fuzzy logic has recently been implemented into decision support tools [92]. Linear programming has seen repeated interest, most recently by Lambrecht and Thissen [93] who created a material flow based optimization tool. Zhu et al. [94] also developed an optimization scheme, and encoded intelligent feedback loops to enable real-time upstream changes in response to downstream conditions. The tool can assist in determining the most optimal power generation and distribution scheme at an auto assembly plant. Likewise, Gould et al. [95] simulated the material flow during production planning. A case study demonstrated the use of a comprehensive search algorithm (CSA), a variant of a generic algorithm, to calculate the minimum changeover cleaning time. Lee et al. [96] developed a tool to simulate product life cycle evaluation and to manage information flows. To date, the tools reported in literature have focused primarily on product and system level assessment, a conceptual legacy of LCA. More recently, tools emerged for UMP modeling. Naidu et al [97] developed a tool to aid the selection of superior sustainable processes using multi-criteria and piecewise comparisons. Eastwood et al. [98] developed a methodology to assess manufacturing of alternate product designs using normalized metric scores. Garretson et al. [99] built upon the methodology reported by Eastwood and co-workers to develop a tool for assessing alternative process plans for a given product. Chen et al. [47] noted there were over 50 tools available as of 2010, and at least 12 that met their guidelines in part for a "good" tool. Despite the recent advancements, Moldaskva and Welo [100] concluded no "silver bullet" (generalizable and holistic) sustainability assessment tool has been developed.

One of reasons for this lack of a "silver bullet" tool could be attributed to the difficulty of combining methods for sustainable UMP assessment with system and operational assessments. In fact, Gediga [101] was among the first to note that ignoring process-related influences reduces LCA accuracy. An approach to addressing this challenge was reported by Duflou et al. [11], Overcash and Twomey [38], and Kellens et al. [102], [103], and integrates unit process modeling and life cycle inventory approaches. Diaz et al. [104] used this method to evaluate the energy consumption and related CO_2 emissions of two machines. They used process data within EIO-LCA to calculate manufacturing energy consumption. While work progresses towards implementing this method into a useable tool [105], a review of the literature reveals that capable tools are lacking. Mani et al. [106] identifying this gap, developed a framework with the goal of assisting the research in developing such tools. Their framework evaluates product life cycle impacts by aggregating product, process, and system level data. The framework also connects the disparate indicator sets at various design and production system levels and recommends relevant datasets, methods, tools, and standards for holistic evaluations. Recent developed standards [107], have begun to fill the need for scaffolding holistic tool development. Standards have yet to make an impressionable dent in the dearth of tools in the literature, however.

This literature review on this topic reveals the sense that as more metrics and measurement methods have been introduced and the process flows been made more complex [108], the number of disparate, non-integrated tools available to aid sustainability assessment for decision makers has multiplied [47], [109]. Winneback [110] serves as a good example. The ineffectiveness of available methods and tools to assess their problem of selecting the superior sustainable product prompted the development of a new method and tool. Their new assessment method solved the problem at hand, but was developed at the expense of exacerbating the overabundance of sustainable measurement methods and tools. Ahi and Searcy [108] found 2555 unique metrics reported in literature, and most were reported only once. They concluded that there is no broad agreement on a common set of metrics, even if the analysis method and data requirements are similar. In light of this situation, Chen et al. [111] presented a qualitative tool employing a questionnaire to aid SME decision makers in navigating through the available indicator sets for factory assessments. This tool does not cover other levels of manufacturing. Thus, the disarray within the field of sustainable measurement science is evident. The profusion of indices, proposed metrics, and measurement tools and methods marks the seriousness with which the research community views sustainability. However, from the perspective of industry, these tools tend to be limited in relevancy since they are either too narrow in focus, and thus myopic, or too broad in focus, and therefore inaccurate [112]. Furthermore, the tools often do not consider the technical or cultural maturity of the organization and, thus, contain no provisions for adaptability [81]. A need has arisen for simple, easy-to-use measurement methods and tools that are standardized, well-rounded, and well-communicated to individual companies [113]. In addition, they must be scalable to meet the maturity of companies' sustainability endeavors.

Process Modeling

This section reviews the literature on process modeling by first defining the term and summarizing mathematical approaches to modeling the transformation of inputs to outputs.

Next, this section presents the benefits of process modeling for decision-making. Finally, current research trends and identified challenges are reviewed.

Process modeling (or process characterization) is inherent to sustainability performance assessment. Process modeling requires identifying key inputs and outputs of a process, collecting data over the operating range, estimating steady state behavior, and modeling the parametric relationships (Mani et al., 2014). In a UMP model developed through process modeling, a workpiece is transformed as inputs (e.g., water and energy) are converted into outputs (e.g., waste water and heat). This transformation of the workpiece imparts value. It also produces waste in the form of scrap and potentially harmful emissions that can indicate sustainability performance [42]. Model evaluation allows for analysis of product and process designs in search of performance improvement [114].

UMP modeling often undertakes one of two approaches: a theoretical investigation of the mechanistic relationships that describe the physics of workpiece-process interactions, or experimental observation and empirical modeling. The first process models used theoretical physics to estimate the impact of selected environmental indicators [115], though most subsequent models are empirically based. One of several approaches can be taken to understand the physics of UMPs. Gutowski et al. [116] and Li and Kara [117] developed UMP models to predict energy use based on process characteristics. Qureshi et al. [118] characterized machining energy consumption through an empirical relationship using process parameters. While it is common to empirically characterize process level interactions, other authors have investigated energy prediction through closer inspection of machine parameters using kinematic and mechanistic approaches [119]–[121]. As UMP models were developed to assess processes individually, other approaches emerged to select superior machines and processes from competing alternatives. Avram [122] proposed using AHP to compare machines on the basis of cutting and machine parameters. Doran et al. [123] assessed sustainability performance of competing additive and subtractive processes based on process and product design parameters to quantify a set of metrics. Concerns arose about whether the proposed models were accurate. Diaz et al.

[120] found a previously reported energy model [117] was accurate by investigating the effect of varying parameter settings for a different brand of machine tool. The challenge remains to convince industry practitioners that the benefits of these modeling approaches are worth the investment.

The slow adoption of process modeling can be partially attributed to a lack of awareness of its benefits. Arinez et al. [124] noted that the benefits of process modeling extend to improving LCA results. LCA is well known in manufacturing, however connecting process models to overarching performance modeling efforts requires understanding the dynamics of multi-level relationships among products, processes, and systems. Yoon et al. [125] proposed focusing on understanding machine life cycle impacts and mapping them to product, process, and system-related impacts. For example, the authors suggested machine lifecycle energy consumption could be reduced by adjusting toolpaths, process parameters, and production schedule. Umeda et al. [126], argued that systematic planning methods are needed to overcome the challenge of connecting process models to larger modeling efforts. Recognizing this, they proposed changes to the traditional structure of life cycle engineering to include an integrated life cycle planning phase. Another challenge of aggregating process models to evaluate system-level performance is understanding and controlling model uncertainties. Campanelli et al. [77] demonstrated how uncertainty could be quantified when synthesizing UMPs into LCI. Others have quantified and predicted uncertainty in UMP models by incorporating Bayesian Networks [127] or Monte Carlo simulation [128].

More recently, multi-level models have been developed using a unit process life cycle inventory approach (UPLCI) [11]. UPLCI is defined as a reporting format [38] that contains an overview of the process, literature data and references, a parameter selection of the process, life cycle inventory (LCI) energy calculations, and LCI mass loss calculations. The method is intended to bridge the gap between UMP modeling and LCA and has been used to model the energy and material flows of laser sintering and stereolithography [129], grinding [130], and other processes to more transparently and accurately determine the environmental impact of the respective processes. UPLCI was later folded into the CO2PE! framework as a complementary approach. Where the CO2PE! initiative offers an in-depth approach to LCA, supporting the diagnosis of the environmental impact of UMPs, UPLCI is a screening approach intended to provide datasets for product LCA [102].

Others have worked to improve UMP modeling efforts through aids in benchmarking [131], or focusing only on waste, energy, and materials [71] as these three categories are responsible for the majority of environmental impacts of manufacturing processes. In an effort to extend process modeling to supply chain activities, Kremer et al. [132] reasoned that process modeling fails in industry applications due to its exclusion of "what if" analysis when selecting suppliers, and can be attributed to the computational complexity involved in considering all decision variables. To consider suppliers and alternative processes as floating variables requires large volumes of information and data, which can be overwhelming to gather and assess, manually. Thus, research has looked for ways to make manufacturing smarter through automated data gathering and model-based analysis and decision making for a range of performance metrics.

Smart manufacturing is seen as a way to merge business interests for high quality, low cost products, with interests for sustainable products, using information sciences. To move manufacturing in this direction requires first developing frameworks and standards for modeling information to bolster the accuracy, robustness, and scalability of current process modeling tools and allow for future tool development. Information modeling tracks the changes to parametric data within a process as the workpiece transits from input to output states. Mani et al. [133] noted the lack of understanding of the information transformations occurring within the "black box" of UMPs hinders the scalability of developed models. To identify information transformations in a manner capable of addressment in tools requires borrowing information modeling techniques from other research fields. Narayanan et al. [134] proposed following the Zachmann framework to develop information models, as it encapsulates all levels of information transfers. Romaniw et al. [135] proposed using

SysML as a modeling tool to assist in creating adaptable process modeling applications. SysML, and its complement, UML, are information modeling languages that together cover all aspects of information flow within a hardware/software environment. Breaking manufacturing information modeling into its distinct levels, Eddy et al. [136] proposed an information model for products, while Zhang et al. [137] proposed one for processes, though none have been proposed for manufacturing systems. Ontologies define the types and relationships between the entities within an information system and have been proposed to facilitate manufacturing information modeling. Hai et al. [138] proposed an abstract level Web Ontology Language (OWL) and XML schema for information modeling. Similarly, Zhang et al. [139] formalized the knowledge of a UMP by combining OWL with Semantic Web Rule Language (SWRL) to enable reasoning on semantics and process knowledge.

Storing the information and process models developed for UMPs has also gathered attention, since a corpus of information holds little value if it cannot be readily stored and queried. Several authors have stated the need and demonstrated the value of repositories capable of handling data storage and structure for pull into process- and system-level assessment models. In the product design phase, Bohm et al. [140] demonstrated the value of integrating LCA results with component information repositories sustainable product design. Verrier et al. [141] presented a repository for lean and green benchmarking company assessments. Lee and Lee [142] developed a classification scheme for a proposed repository of sustainability papers for quick and easy access by industry, while a related repository was proposed and developed for the warehousing of sustainability performance metrics and indicators [7], [31].

From the foregoing, it can be seen, while the research into manufacturing process modeling has advanced [143], [144], the prevailing methods and tools employed by small and medium size enterprises to characterize and assess the sustainability performance of their processes remain diverse and *ad hoc.* This literature review supports the findings of Labuschagne and coauthors from over a decade ago [112]. First, there are challenges in determining the most accurate method for modeling a given process; second, there are challenges in allocation and aggregation between manufacturing levels; and third, there is a lack of simple tools to model UMPs, link them, and aggregate them to support LCA. The roundtable dialogues described above were designed around these central concerns. The intent of the dialogues was to discover whether industry concerns mirror those identified in the literature. Aligned concerns offer potential direction for the development of standards, whereas challenges that are not equally shared would require further investigation to determine the most appropriate means of being addressed.

Systematic Literature Review

The systematic literature review (SR) method complements a narrative review by objectively identifying the most active research topics, authors, institutions, and journals in a particular field. Here, this review of sustainable manufacturing quantitatively evaluated publication data from literature published between January 1, 1994 to June 30, 2016. The method for conducting this SR followed that reported by Mirkouei et al. [145].

Using the Web of Science™ (Thomson-Reuters) database, three keyword sets were developed to query the international conference and journal articles between the selected dates. Publications that came back "true" for all constructors (keyword queries operate under Boolean logic) were sorted into separate databases. Bibliometric data was exported as text files from Web of Science™ to be read and mapped in VOSviewer Software [146] for the purpose of visualizing the bibliometric data.

- Keyword Set 1: (Sustainability OR Sustainable) AND (Metrics OR Indicators) AND (Process OR Product OR Factory OR System) AND (Manufacturing)
- Keyword Set 2: (Sustainability OR Sustainable) AND (Process OR Product OR Factory OR System) AND (Tool OR Method) AND (Manufacturing)
- Keyword Set 3: (Sustainability OR Sustainable) AND (Process OR Product OR Factory OR System) AND (Modeling OR Simulation) AND (Manufacturing)

Keyword Set 1 targeted publications involving metrics and indicators, Set 2 targeted measurement methods and tools, and Set 3 targeted process modeling. Keyword Set 1 returned 235 documents, Set 2 returned 282 documents, and Set 3 returned 263 documents. There were 13 total documents in common. Table 1 provides a breakdown of all returned documents and pairwise comparisons. The pairwise comparisons were done to assess the level of overlap between keyword sets. The pairwise comparisons indicate a large degree of overlap between Keyword Sets 2 and 3. As mentioned in the narrative review above, most studies developed a method or tool for manufacturing modeling or simulation (e.g., of a process or system). The absence of a strong overlap between Keyword Sets 1 and 2 and Keyword Sets 1 and 3, was unexpected. A few possible explanations are that the term "indicator" or "metric" is replaced with another (e.g., the use of process flow instead of metric [147]) or report specific metrics such as energy consumption but omit the term "metric" or "indicator" [148]. Alternatively, it is possible that the limitations of this method of literature review are beginning to surface.

Table 1: Database generation and pairwise comparison

Database	**Records**	**Database**
#1	235	Keyword Set 1
#2	282	Keyword Set 2
#3	263	Keyword Set 3
#4	13	Keyword Set 3 AND Keyword Set 2 AND Keyword Set 1
#5	598	Keyword Set 3 OR Keyword Set 2 OR Keyword Set 1
#6	32	Keyword Set 1 AND Keyword Set 2
#7	26	Keyword Set 1 AND Keyword Set 3
#8	137	Keyword Set 2 AND Keyword Set 3

Each keyword set was used to search the Web of Science database, restricting the search to the Topic field, which includes the document title, authors, and keywords. For Set 2 and

Set 3, over 800 documents were returned, and the majority of the returned documents were unrelated to the desired topic. Thus, in the next round, the (Process OR Product OR Factory OR System) keyword constructor was instructed to search only the Title field for these two sets to reduce the number of returned documents, which are reported here. This search was repeated for Set 1, and only returned three results.

Figure 4 presents the search results for Keyword Set 1 as density maps of the bibliometric coupling analysis between documents made using VOSviewer Software. Bibliometric coupling analysis determines the relatedness of documents based on the number of references they share. The documents clustered around warm colors (red and orange) have a high number of mutual citations, while documents in regions of cool colors (blue and green) indicate those with fewer mutual citations with other documents returned by the search. In the maps, text size increases with an increasing number of co-citations. Four hotspots appear in the density visualization for Set 1, which can be characterized as supply chain sustainability, life cycle assessment, green chemistry, and sustainable manufacturing. The results suggest that research within each of these subfields is highly coupled, but does not necessarily extend far beyond the local hotspot region.

The density hotspots in Figure 5 (Keyword Set 2) are more tightly integrated than observed for Set 1. The main research approaches in sustainable methods and tools appear to focus on machine and process energy assessments (Zhong, Yoon, Peng), supply chains (Kremer), life cycle engineering and industry ecology (Despeisse, Umeda).

Figure 6 shows the resulting density map for Keyword Set 3. Modeling and simulation show stronger integration, but multiple hotspots. In fact, five hotspots can be discerned in Figure 6. Starting from the top and moving bottom right, these five hotspots correlate to published research in sustainable engineering management (Wu, Hall), supply chain management (Dubey), life cycle engineering (Despeisse), sustainable manufacturing (Vimal), sustainable machining (Peng), and sustainable process planning (Li).

Web of Science^{TM} includes internal tools for further analyzing search results. Three tables were generated using these tools to list the top ten authors, organizations, and source titles for each keyword set (Tables 2, 3, and 4). The names that appear in each keyword set, as well as those that appear only once, are of interest. Table 2 indicates that multiple authors are active within each keyword set, and others only within one. Table 3 indicates that the institutions conducting this research are globally distributed with strong concentrations, depending on topic area, in the United States, East Asia, South Asia, and Western Europe. Table 4 shows that the Journal of Cleaner Production, the International Journal of Production Research, and the International Journal of Advanced Manufacturing Technology are the three journals with the largest number of citations for each keyword set. This seems to indicate that these three journals are the flagship venues for research in sustainable manufacturing for Elsevier, Taylor & Francis, and Springer, respectively.

Next, the datasets for each of the three keyword sets were combined, resulting in a total of 598 unique documents (of which 229 were readable). These documents were assessed on the basis of their source. Figure 7 visualizes the frequency of mutual citations in each journal pair on a normalized basis (thicker lines indicate more mutual citations). Of the sources returned, only ten were cited by ten or more other documents. Connections were normalized to emphasize relationships in favor of strength by raw numbers. Frame size is proportional to total number of sources, i.e., larger frames indicate more sources cited from that journal. Figure 7 identifies the Journal of Cleaner Production as being at the center of the sustainable manufacturing research "web." The combined dataset was queried to identify the institutions collaborating on research in the domain. Of the 229 organizations, ten had jointly published nine or more documents. Figure 8 below displays the normalized network map between these institutions, indicating three strong networks: a West-Midwest university connection, a collaboration between Wayne State University and the United States Environmental Protection Agency (EPA), and a proximity relationship between NIST and the University of Maryland. Within the combined dataset, eight authors authored eight or more joint publications. Figure 9 presents the authors groupings and mapping relationships. Links have been normalized to emphasize relationships, rather than the number of mutual citations.

The results of the SR demonstrate that the sustainable manufacturing field is active and diverse, but as shown in the density maps created for each keyword set, links between the various research groups could be strengthened to create more coherency. The density maps echo the findings of the narrative review. In fact, within each topic area, e.g., metrics, measurements, or models, more than one research hotspot exists in isolation from the others. The density map for the process modeling area, however, seems to represent more a more interconnected research community. The disparate nature of the communities implies that research within one subfield is not being reported by others. Possible ramifications are that prior work could be duplicated or key research gaps could be left unidentified or unaddressed. As a result of the narrative and systematic literature reviews, the most active journals, authors, and organizations in sustainable manufacturing topics have been identified. This can aid academic and industry researchers in identifying potential gaps, defining prior related work, and investigating sustainable solutions to a given problem.

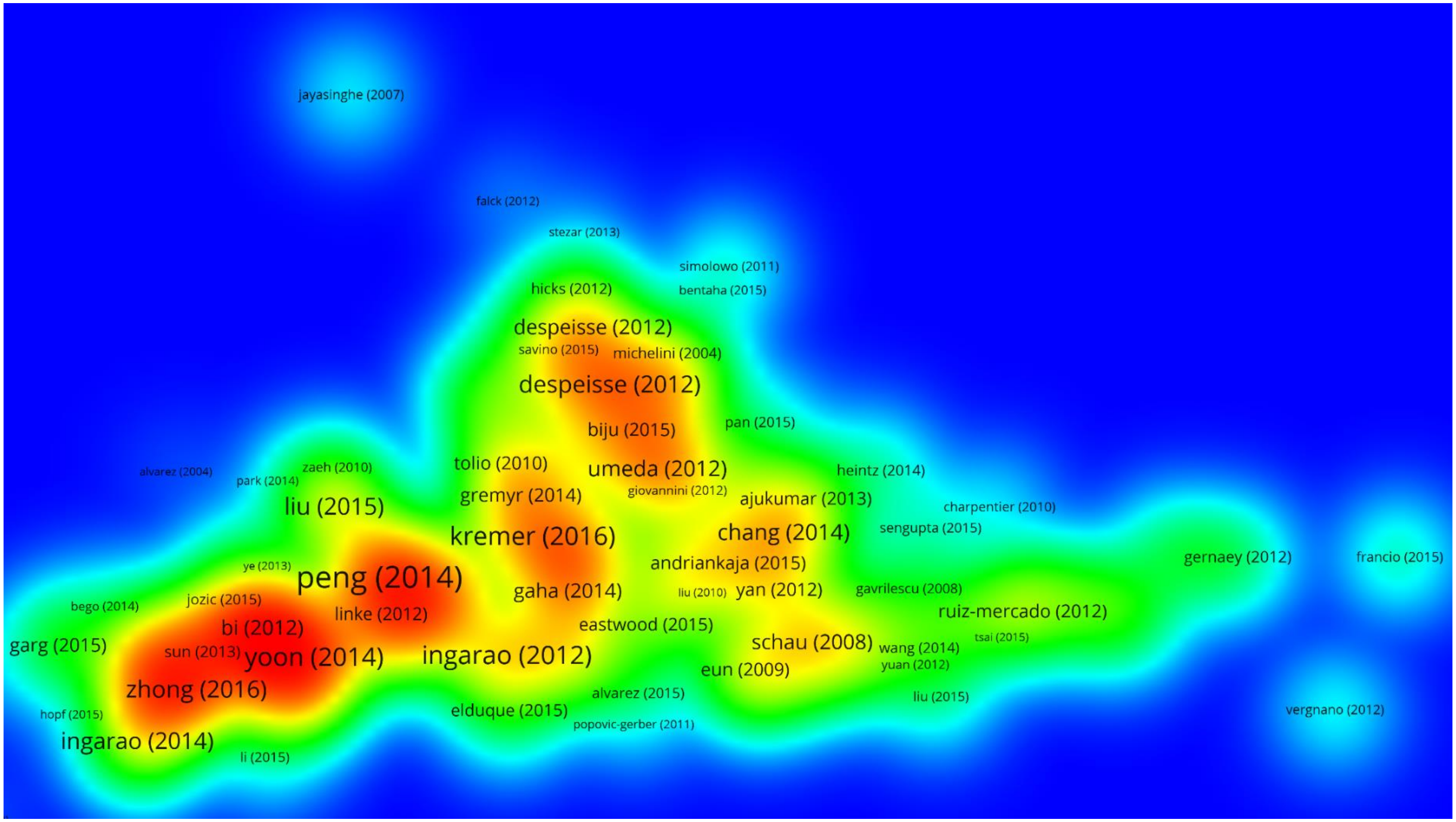

Figure 4: Density map of authors in field of sustainable manufacturing metrics and indicators

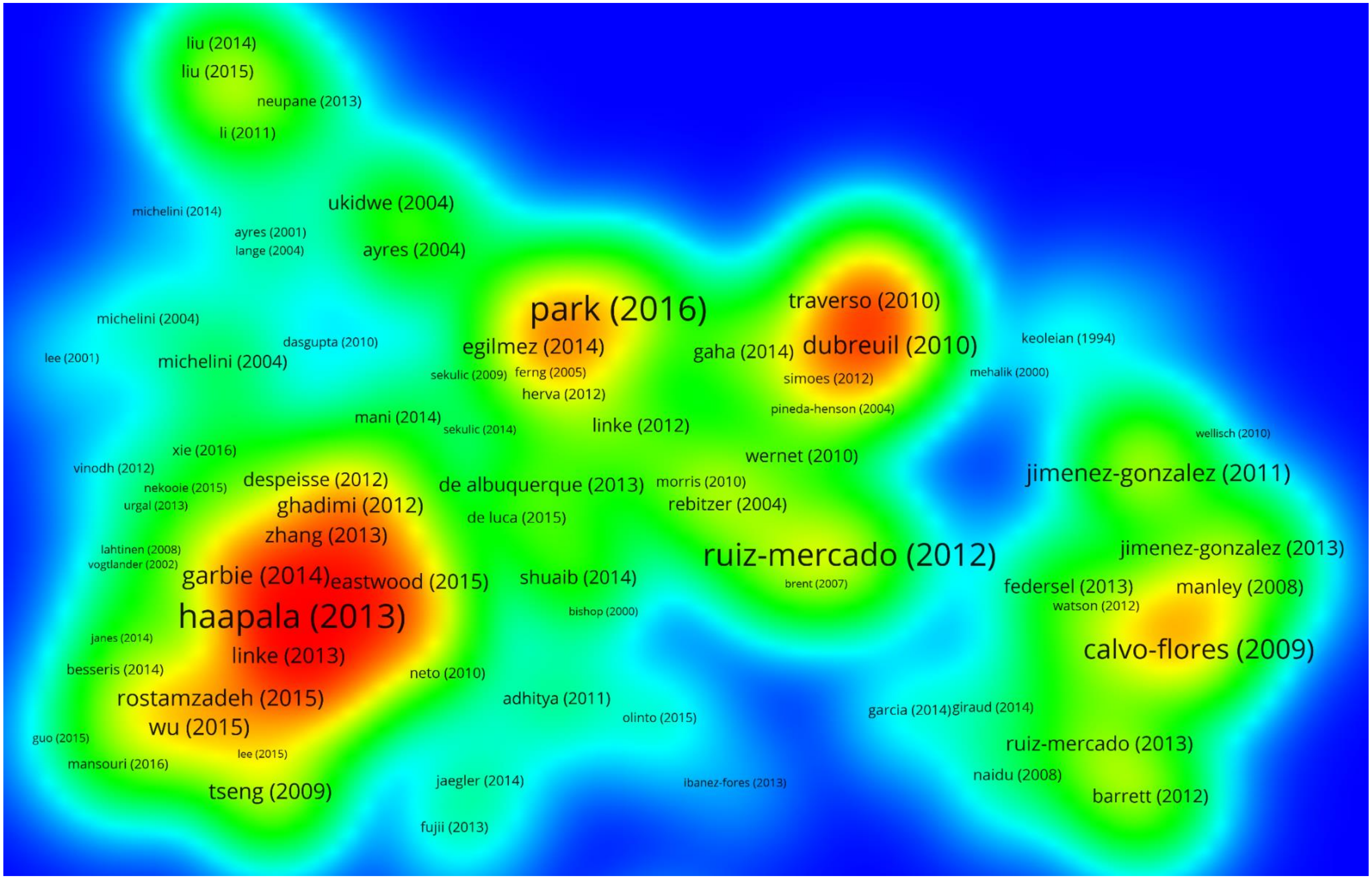

Figure 5: Density map of authors within field of sustainable manufacturing methods and tools

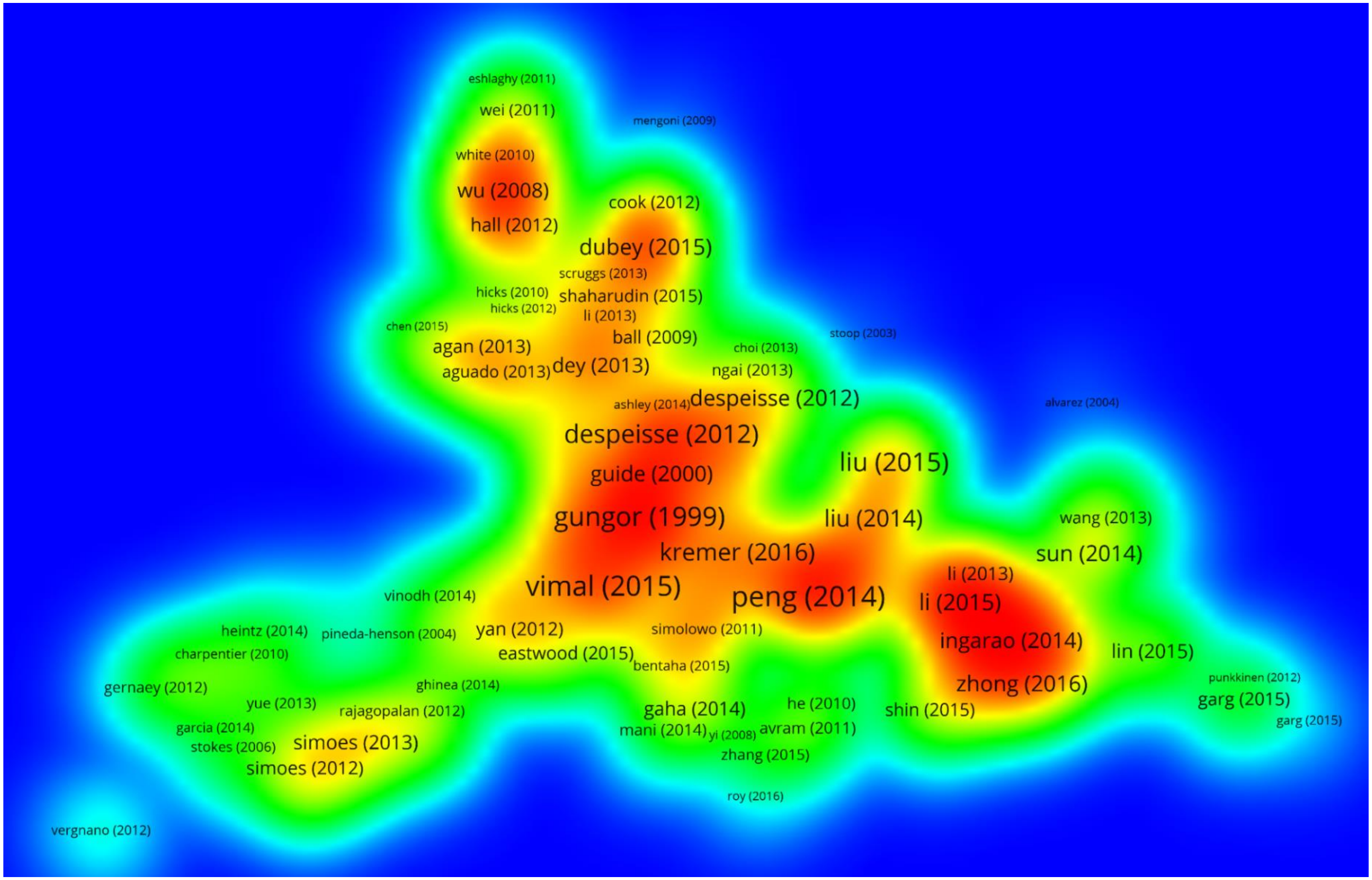

Figure 6: Density map of authors within field of sustainable manufacturing process modeling

Table 2: Ten most active authors for each keyword set

Keyword Set 1		Keyword Set 2		Keyword Set 3	
Authors	**Total**	**Authors**	**Total**	**Authors**	**Total**
Jimenez-Gonzalez C.	6	Sutherland John W.	6	Li Lin	6
Mani Mahesh	5	Li Lin	6	Vinodh Sekar	5
Lyons Kevin	5	Gonzalez Michael	5	Evans Steve	5
Kucukvar Murat	5	Sun Zeyi	4	Sun Zeyi	4
Haapala Karl R.	4	Smith Raymond L.	4	Ball Peter D.	4
Egilmez Gokhan	4	Ruiz-Mercado Gerardo J.	4	Zhang Heng	3
Dornfeld David	4	Kara Sami	4	Sutherland John W.	3
Vinodh Sekar	3	Duflou Joost R.	4	Simoes Carla L.	3
Tseng Mitchell	3	Zhang Hao	3	Shin Seung-Jun	3
Tatari Omer	3	Matthews Jason	3	Roy Utpal	3

Table 3: Ten most active institutions for each keyword set

Keyword Set 1		Keyword Set 2		Keyword Set 3	
Organizations	**#**	**Organizations**	**#**	**Organizations**	#
NIST	9	US EPA	6	University of Illinois	7
US EPA	8	University of Illinois	6	Hong Kong Polytech University	6
University of Kentucky	6	University of California, Berkeley	6	Cranfield University	6
University of California, Berkeley	5	Purdue University	6	University of Tokyo	5
Oregon State University	5	University New S Wales	5	India National Institute of Technology	5
University of Maryland	4	University of Bath	5	Delft University of Technology	5
North Dakota State University	4	NIST	5	Wayne State University	4
GlaxoSmithKline	4	Katholieke University of Leuven	5	University of Cambridge	4
University of Waterloo	3	Cranfield University	5	University of Bath	4
University Teknology of Malaysia	3	University of Wisconsin	4	Syracuse University	4

Table 4: Ten most cited journals for each keyword set

	Source Titles	Total
Keyword Set 1	Journal Of Cleaner Production	40
	International Journal Of Production Research	14
	International Journal Of Advanced Manufacturing Technology	11
	International Journal Of Life Cycle Assessment	8
	Journal Of Manufacturing Systems	7
	Proceedings Of The Institution Of Mechanical Engineers Part B Journal Of Engineering Manufacture	6
	International Journal Of Computer Integrated Manufacturing	6
	Cirp Annals Manufacturing Technology	6
	Sustainability	5
	International Journal Of Production Economics	5
Keyword Set 2	Journal Of Cleaner Production	52
	International Journal Of Advanced Manufacturing Technology	13
	International Journal Of Production Research	8
	International Journal Of Computer Integrated Manufacturing	8
	International Journal Of Precision Engineering And Manufacturing	7
	International Journal Of Life Cycle Assessment	7
	Proceedings Of The Institution Of Mechanical Engineers Part B Journal Of Engineering Manufacture	5
	Journal Of Manufacturing Systems	5
	Computers Chemical Engineering	5
	Cirp Annals Manufacturing Technology	5
Keyword Set 3	Journal Of Cleaner Production	40
	International Journal Of Production Research	14

	International Journal Of Advanced Manufacturing Technology	11
	International Journal Of Life Cycle Assessment	8
	Journal Of Manufacturing Systems	7
	Proceedings Of The Institution Of Mechanical Engineers Part B Journal Of Engineering Manufacture	6
	International Journal Of Computer Integrated Manufacturing	6
	Cirp Annals Manufacturing Technology	6
	Sustainability	5
	International Journal Of Production Economics	5

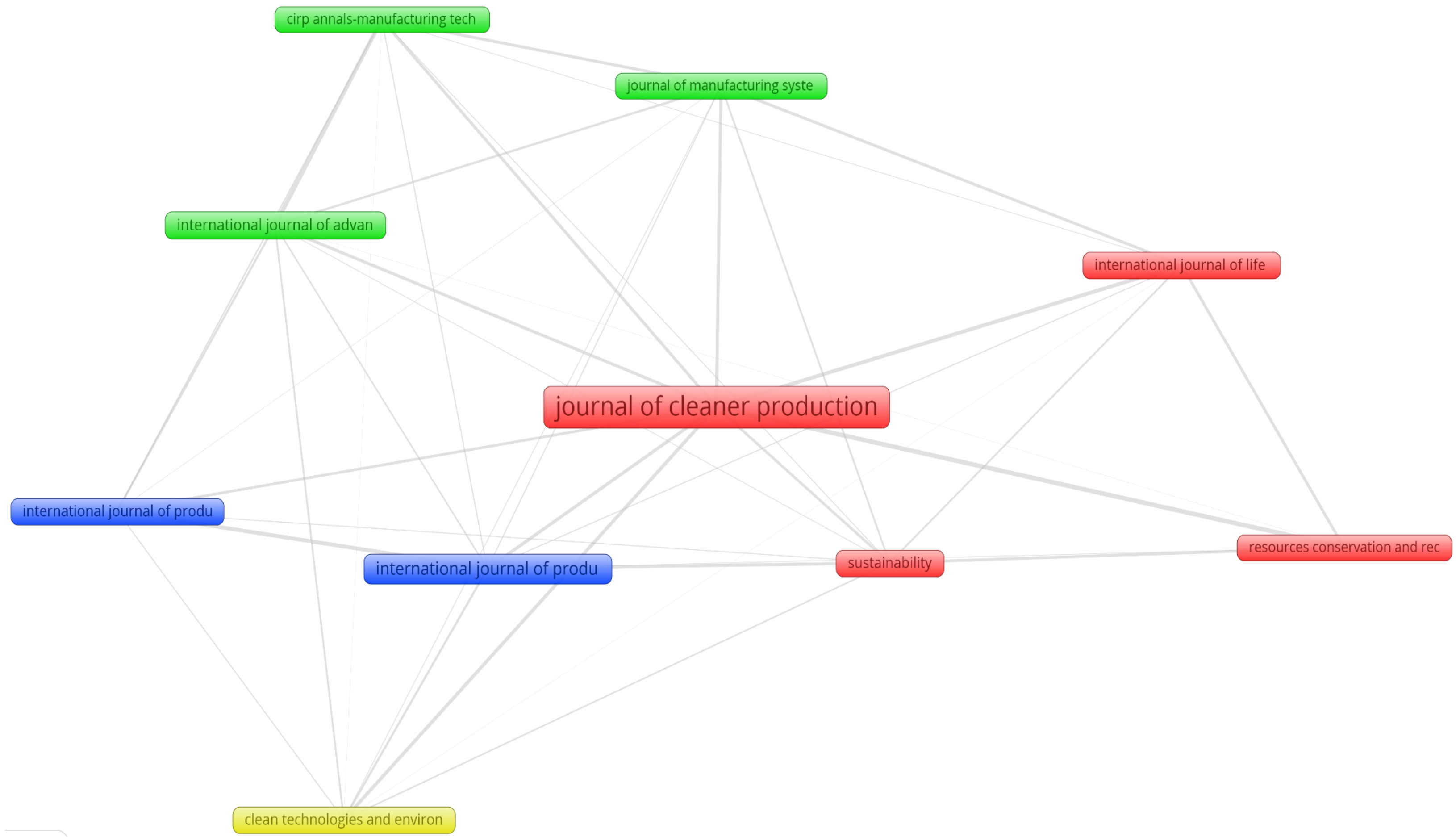

Figure 7: Top ten journals by citations

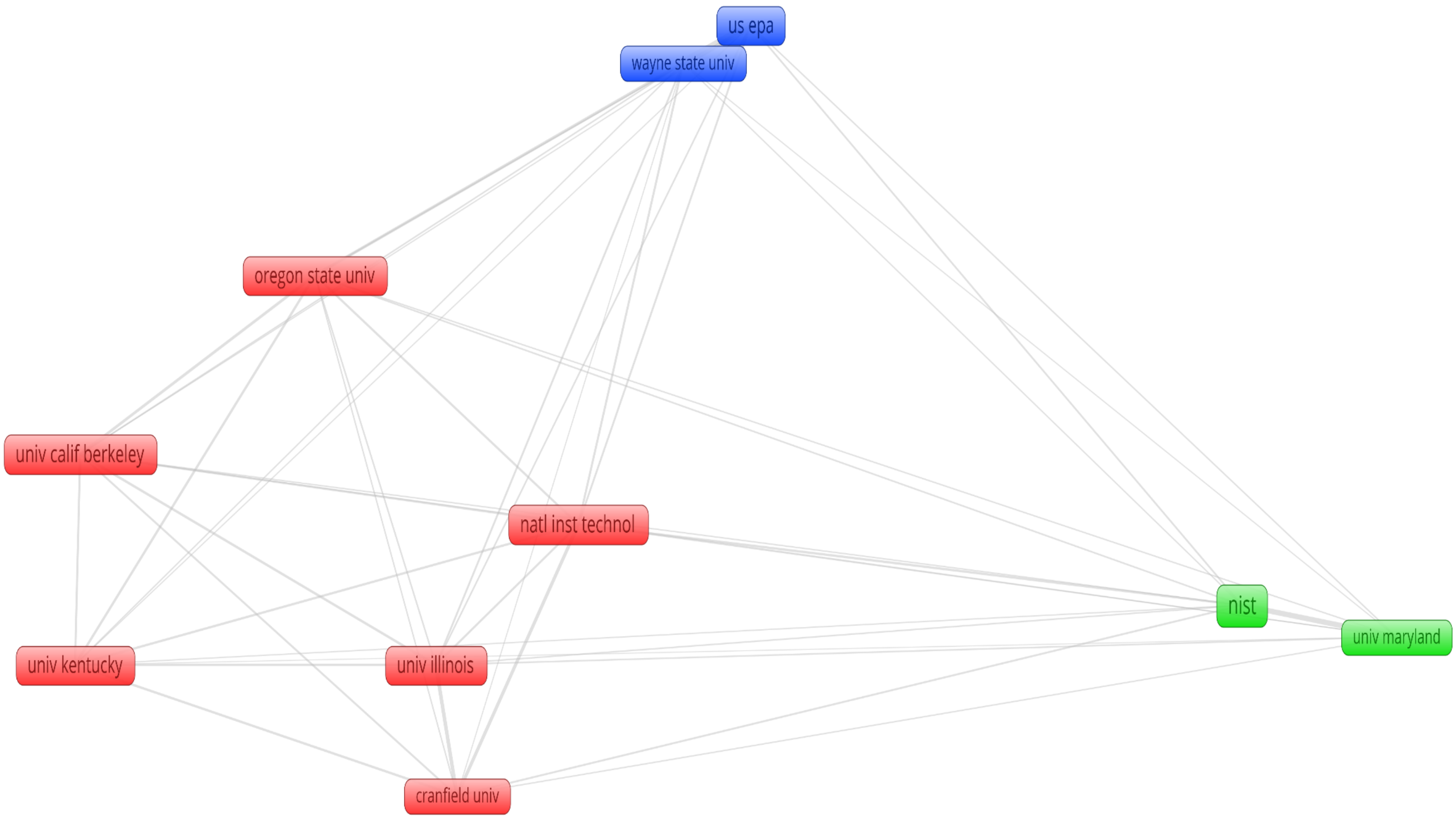

Figure 8: Top ten institutions with more than ten publications

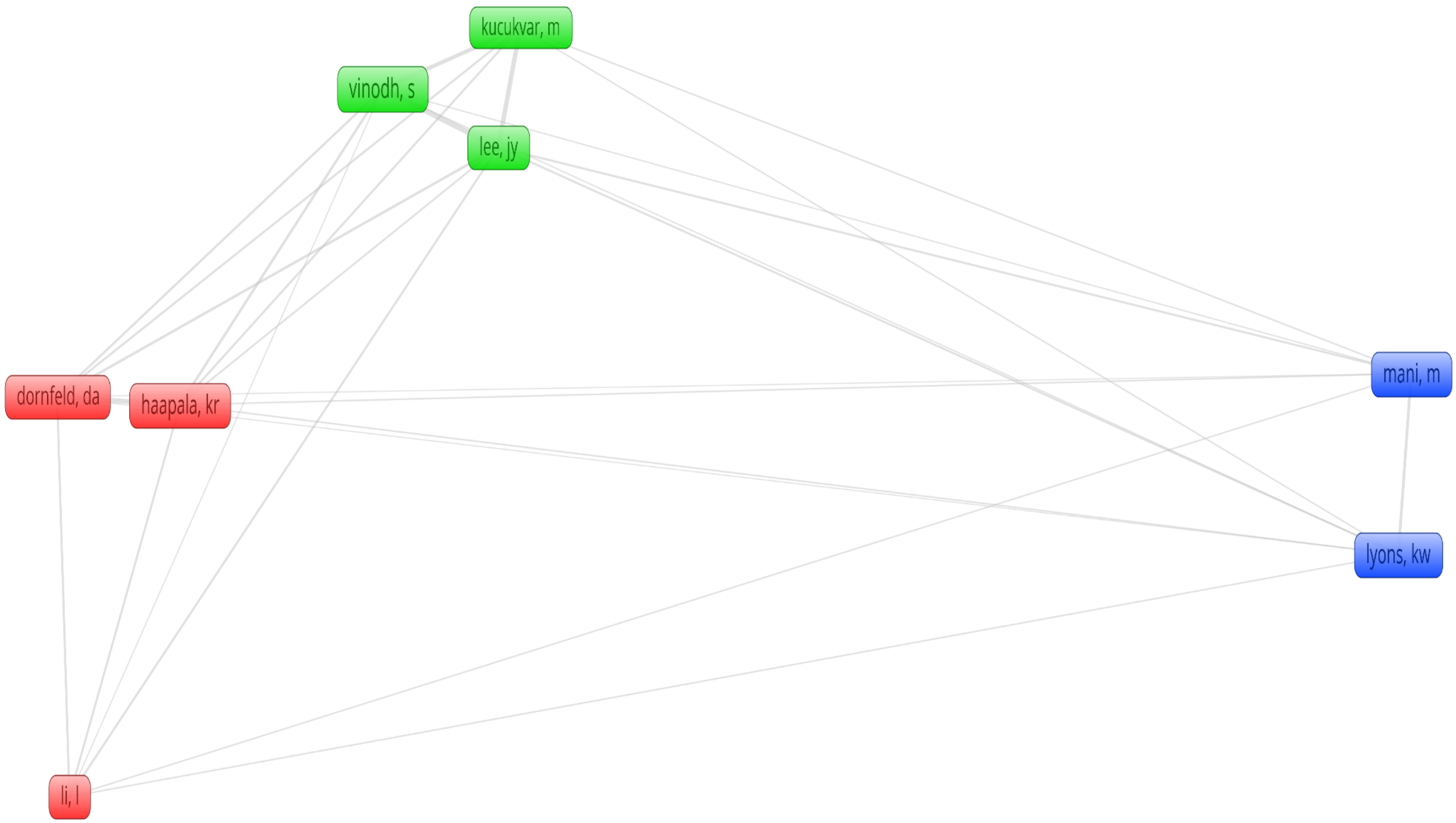

Figure 9: Authors with eight or more publications. Links are normalized and represent number of shared references

Roundtable Findings

The findings of the roundtable meetings are presented in two subsections below. In keeping with the roundtable agenda, Section Metrics & Measurements covers both manufacturing metrics and measurement science topics, as this constituted the discussion during the first dialogue session. Likewise, Section Manufacturing Process Modeling covers manufacturing process modeling, in keeping with the second dialogue session.

Metrics & Measurement

When asked what approaches their companies used to understand the effect of process-level issues on system-level performance, participants identified product quality and labor costs as the most important metrics. The companies represented at the roundtables used a variety of methods to assess the quality of their products (e.g., defect detection systems, flow analysis, data analysis, and on line inspection). In addition, a common performance measure adopted was velocity, or throughput, of the system. Quality standards are typically set industry wide, but the methods to measure quality are unregulated. For example, a representative from the wood products industry mentioned their company built windows in two different facilities. The final quality grade was the same, but the measurement method differed.

On the topic of sustainability performance, the consensus was that most sustainability assessments focus only on system level environmental and social indicators and metrics and are commonly conducted in consultation with LCA practitioners. The intent of these assessments is to identify areas for improvement, though these can become quickly exhausted if the focus is only system level indicators (e.g., factory energy consumption and total waste). To identify new improvement opportunities requires tracking and reporting process-level data and information. Means of tracking the process-level issues include various types of control and monitoring devices. Historical data is used to identify root causes of process issues and map process responses to control parameters. For example, a carbon nanotube manufacturer required 2-3 years of data to understand process operation.

Another common approach identified was the use of factory floor operator experience, go/no go gauges, and, generally, holding line managers accountable for process control. Identifying and selecting metrics for process-level tracking is often done based on the experience of managers and line operators and only in response to specific problems. The result is that metrics and their related process equations are not standard and often are not documented in a standard manner, if at all, and many metrics rely on a controller's tacit knowledge of the process.

When asked what metrics are of high value and were they originally communicated top down or bottom up, participants identified material waste, labor cost, and quality as some of the most important top down performance indicators. Top down metrics are those imposed by customer demand (e.g., quality, costs, and delivery) and government regulation. Bottom up metrics are designed to meet these top down goals through efficiency gains. A common implicit agreement among participants was that top down drives change, while bottom up discovers opportunities to enact the change. Social indicators are selected to comply with regulations and to meet customer expectations regarding worker safety and consumer health. A few participants added that the perceived risk to the company or the public of an accident influences the selection of indicators. Some are even selecting indicators to gain sustainability minded customers. However, industry continues to struggle with the organizational difficulties of reconciling bottom up with top down indicators and metrics. The same is true for communication of information and goals among different business units.

Oftentimes communication is one sided, with management sending work instructions to shop floor personnel with no intention of receiving feedback. This wall between management engineering and shop floor was widely agreed upon by participants as the largest contributor to system, process, and product issues. Similarly, due to business unit silos and competing goals only a few metrics are standard, with business units oftentimes hosting unique metrics incompatible with other business units. The result is that while some business units may be starved of data, others are inundated. Furthermore, the interpretation of this data relies heavily on the experience and tribal knowledge of engineers and managers. This experience has been gained either from testing, inspection, or validation or is based on tacit knowledge internal to the company. There was common agreement that this is both a weakness and a strength, as it both hinders and improves competitive advantage. Standards (ISO, AS) were discussed by a few participants as a means of addressing the data and metric disparity, while also assisting in turning tacit to explicit knowledge, by centralizing a common core of measurements, metrics, and indicators. To encourage the addition of sustainability, some companies are looking to sustainability indices (e.g., Dow Jones Sustainability Index) for guidance and benchmarking. Furthermore, there was common agreement that it can be difficult to engage shop floor personal to enact top down initiatives. A few participants noted that in their experience, incentives such as cash handouts or dashboards can act as pushes to overcome these barriers.

Tools identified included using excel to collect and analyze process level data for selected performance indicators. Data is collected through data acquisition software (e.g., SCADA) or manually by hand. Tools identified including commercial software packages, six sigma, and lean tools for quality assessment and throughput tracking. Others looked to ERP and MES to assist with sustainable initiatives such as material and energy consumption. It was noted that while energy is not of high importance, material consumption is, thus participants were quick to agree that sustainability is a shared desire of industry, but must be expressed in terms of cost reductions and its value to the customer. For example, one participant frankly shared a story of a product designed for sustainability that went undesired by customers. When modeling processes, engineers tailor the model to the needs of the company and its chosen indicators. Further, the modeling approach is often unique to the company and/or the engineer. This inhibits the free sharing of process models, but also acts as intellectual property protection.

In summary, most metrics and measurement methods are selected on the experience of the managers. Repeated on a large scale, this compartmentalization leads to a lack of uniform and formally-defined metrics and methods to capture manufacturing process data across an industry. This lack of standardization inhibits industry's ability to benchmark and collectively learn best practices. Furthermore, without standardized metrics and measurements, standardized process models cannot be successfully created.

A few participants noted that a culture of independence and autonomy at manufacturing sites reduces the ease of information transfer, especially with regard to communicating sustainability initiatives and top-down performance indicators. Others noted that this culture of autonomy extends to subgroups within manufacturing facilities. As a result, process level issues and solutions often remain isolated to the subgroup who conceived them and do not contribute to system level assessments.

The topic of manufacturing process modeling is presented in the next section, which was the focus of the second dialogue session.

Process Modeling

The first question asked of participants gathered high-level input on the perceived value of manufacturing process modeling and the use of tools for manufacturing process modeling. One of the more prominent values expressed was the increased prediction accuracy compared to control or monitoring only. The literature review concluded that UMP modeling has the capability to increase the accuracy of sustainability assessments by quantifying resources in the form of labor and machine hours, equipment utilization, energy, and water use to produce a product or perform a process. However, due to the number of competing methods and tools advocated in the literature, none of which allow for comprehensive process and system analysis, industry is loath to wholeheartedly adopt any of these methods or tools. For example, participants noted that other time-tested techniques (e.g., Six Sigma and lean techniques) or tools (e.g., ARENA and Aspen) accomplish the desired quality and accuracy goals of different industries. Lean techniques and related concepts, such as value stream mapping, kaizen, and muda, were specifically mentioned for their abilities to identify improvement opportunities. In particular, participants noted that the capture of inputs, outputs, and controls (characterization) of process models is commonly achieved using MES.

This reluctance to adopt non-standard methods and tools extends to the adoption of new resources. Sustainability performance improvement is often viewed as an add-on to the conventional focus on labor and material efficiency. This view underlies the reluctance to adopt new methods or tools, or to invest internal resources for their development. Resources are sometimes dedicated to process modeling activities, which are not specifically targeted at sustainability assessment, and include software for computational fluid dynamics (CFD), input-output mass and energy balances and process flow analysis (e.g., Aspen), environmental impact analysis (e.g., SolidWorks Sustainability), solid modeling (e.g., Creo), and specialized tools developed in MS Excel. Process failure modes and effects analysis (P-FMEA) is used, but does not have suitable off-the-shelf tools for sustainability analysis. In most cases these tools are not equipped to facilitate UMP modeling. The purchase of smart machine tools was noted as a way to improve performance, and allow for machine self-direction. Thus, automating machine tools offers a means to reduce uncertainty and allow more accurate prediction of quality and cost. Most software tools that address sustainable design for manufacturing do not offer the ability to evaluate manufacturing process-level sustainability metrics. Furthermore, these tools often lack accurate and relevant process databases, forcing companies to construct unique internal databases, which can be resource intensive.

Since information contained in databases is specific for a process from which it was collected, its applicability to similar processes in other locations or use environments is limited. To increase information flexibility or applicability, mathematical process models are sometimes developed based on first principles or mechanistic models. If more accuracy is needed, companies turn to empirical process modeling. Model uncertainty is handled using Monte Carlo analysis, and some participants noted seeing Bayesian analysis used in practice. In both cases, these techniques are applied piece-wise to a single chosen process. Moving from the process to the facility, process flow diagrams and material flow analysis are sometimes used for modeling plant layout, plant replication, and plant improvement.

In summary, industry is hesitant to adopt UMP modeling for a number of reasons. First, the sustainability literature shows little cohesion or unison in advocating a common approach to UMP modeling. This makes industry wary to adopt methods and tools that run the risk of obsolescence. Second, industry is aware that the benefits of UMP modeling may not be apparent until after the models have been developed, but the nascent state of UMP research reduces the willingness of industry to invest the resources necessary to create these models

Discussion

Based on a comparison of the literature review and the industry roundtables, a set of identified barriers and recommendations was developed (Tables 5 and 6). This set emerged from comments made by industry participants during the roundtable dialogues. The discussion of the tabulated findings is found in the Research Findings Section. Relevant standards efforts capable of addressing these barriers and recommendations are presented in the Relevant Standards Efforts Section.

Table 5: Identified barriers to the adoption of sustainable manufacturing standards

Manufacturing Metrics & Measurements	
• Current tools do not emphasize usability with their steep learning curves	• Standards cannot address the needed cultural change to address sustainability in a proactive manner
• No standard method exists for combining process and system level indicators in a holistic manner	• Sustainability R&D projects do not receive equal funding within companies
• Current tools and methods do not always show immediate practical change; a necessity for adoption by industry	• Standards do not address the potential for falsification of material or process data by companies
• Recertification of a manufacturing process after modification is a financial barrier to wider standards adoption	• Sustainability metrics included in standards do not address explicitly address quality; a common measure of performance amongst companies and individuals
• Companies and suppliers hesitate to share sensitive process data or models for fear of losing trade secrets or competitive advantage	• Tools and methods will not be widely adopted if they advocate the upgrade or replacement of analogue, but still functional, machinery
• Incorporating new methods, tools, or standards requires large time investments before showing practical results	• Current research lacks a cohesive theory how to evaluate and close the design for manufacturing gap
Manufacturing Process Modeling	
• Regulatory changes can antiquate currently used methods or tool	• Proposed process models risk sub-optimization occurring when only considering least cost manufacturing
• Commercial software packages are costly and fragmented impeding their wide scale adoption	• Standards cannot readily address the difficulty of sharing process models and linking them due to process setup variability and machine age

Table 6: Identified solutions to the adoption of sustainable manufacturing standards

Manufacturing Metrics & Measurements	
• Orient standard metrics to explicitly state cost value to appeal to high level management who are chiefly concerned with maintain cost competitiveness and market share	• Due to the high cost of creating full manufacturing process models, create a "light" version focusing only on primary process drivers to alleviate initial investment concerns
• Make metrics and indicators standard industry wide to facilitate friendly competition and increase supplier participation	• Develop a library of materials and UMPs to aid design for manufacture decision making and to be incorporated into the engineering toolbox
• Make tools with an easy entry version to highlight small improvements and aid in identifying low hanging fruit and to justify larger investments	• Engage shop floor personnel by showing real time feedback on the sustainability performance of metrics through visualizations, such as dashboards
• Any sustainable manufacturing tool should be usable on current equipment (e.g., machine tools) to demonstrate future usefulness	• Incorporate process modeling into the manufacturing step of LCA to increase total model accuracy and identify areas for improvement
• Incorporate traceability into sustainable manufacturing tools as it is frequently requested by manufacturers	• Plan for the introduction of new top down regulations and their impact on product manufacturing
• Clearly and uniformly define tool boundaries and capabilities to reassure industry that they are purchasing and using the correct tool	• Demonstrate an allocation method for system level indicators, such as how occupational health and safety information is directly relatable to product manufacture
• Identify environmental impact drivers using on the line data and not industry or facility averages	• Incorporate accountability of materials and consumables into assessments e.g., including impact of an alternative solvent within an LCA
Manufacturing Process Modeling	
• Consider regional location, access to resources, and laws when conducting LCAs and developing process models. No standard as of yet allows a large degree of localization freedom or adaptability	• Make models and data generated by a standard or government accessible to all e.g., integrate with the Digital Commons or the NREL U.S. Life Cycle Inventory Database
• Future standards development should integrate UMP models back into LCA methods and tools	• Standardize the composability of UMP models such that they do not require soliciting the individuals who created the process models

Research Findings

Comparing the findings from literature with the results of the roundtables illustrates several key findings where literature and industry diverge in theory and practice for UMP modeling. The summarizing conclusion from industry is that product quality appears to be the key process indicator, while labor costs are the key systems indicator. Yet, methods reported in research literature are remiss in incorporating product quality as a sustainable manufacturing performance metric. For example, in a recently proposed sustainability indicator framework to aid small manufacturers, only one indicator measuring defective products was directly related to product quality [149]. Further, this deficiency alludes to a discrepancy between sustainability performance metrics and traditional accounting principles. Few metrics explicitly connect sustainability performance to company cost competitiveness [150]. This is a point emphasized by Engert et al. [151], whose literature review in strategic management emphasized that sustainability must be expressed in terms of costs. Similarly, Ziout et al. observed that this belief is universal, shared among emerging and developing market companies [152]. This dissonance may be accounted for by lack of stakeholder involvement. For instance, in the study reported herein, roundtable participants actively requested continuing the roundtable discussions into later dates to gain clarity on current sustainability improvement efforts and shape the direction of future research. Souza [153] suggested that stakeholder involvement is crucial to the success of sustainable initiatives as it allows fine-tuning metrics and metric relationships. Participants in our study agreed, as they saw the roundtables as being educational and an opportunity to develop future collaboration.

Furthermore, while research literature details many bottom-up metrics, the consensus among larger, more mature industries is that top-down metrics dominate, often dictated by government regulations. Rametsteiner [154] suggested the need for indicator selection to be an inclusive process, noting that indicators must reflect regulatory actions. Recent responses have seen the incorporation of elements of public policy and governance into sustainability tools and methods [155]. According to industry, despite this advancement there is still a deficiency in bottom-up process metrics that satisfy top-down compliance requirements. Industry and academia are working to address these issues, such as with the development of process metrics to aid tracking of social indicators, e.g., worker safety [22]. Even if the above situations were resolved, industry participants adamantly noted that the final hurdle often encountered in conducting sustainable performance assessments is the breadth of available specialized tools. The lack of standardization in sustainability assessment methods has led to a profusion of individual tools encapsulating different methods [156]. One approach to addressing these challenges is through the development of industry-agreed upon standards, as discussed below.

Relevant Standards Efforts

Several current standards capable of addressing some of the identified industry concerns are introduced below. Existing manufacturing standards provide instructions for designers, engineers, builders, operators and decision makers to conduct activities within their fields. They also facilitate communication between stakeholders across different organizational borders. Furthermore, standards facilitate information transfer across borders of the manufacturing system hierarchy and between life cycle phases. Standards are fundamental to advanced manufacturing systems to facilitate the delivery of information to the right place at the right time. Standardization enables automating system responses and permits establishing repeatable processes all sharing common functional understanding. This reduces the cost of adopting new technology.

To this end, ASTM International formed a committee on Sustainability (E60) and a Subcommittee on Sustainable Manufacturing (E60.13) [157]. As a result of their work, the ASTM Guide for Characterizing Environmental Aspects of Manufacturing Processes [18] was developed to address concerns such as those identified in this work. This guide outlines a characterization methodology and proposes a generic representation from which manufacturers can derive specific UMP representations for meaningful sustainability performance analysis. Also, ASTM recently published the Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes, which provides guidance for manufacturers on how to conduct an environmental sustainability study in order to improve their practices [107]. Other relevant standards under development within the E60.13 Subcommittee include:

- Classification for Waste Generated at Manufacturing Facilities and Associated Claims,
- Guide for Integration and Reporting of Environmental and Social Sustainability within the Manufacturing Supply Chains,
- Standard Specification for Net-Negative Landfill Waste Manufacturing Processes.

The vision of these standards is to provide manufacturers with a way to better describe their manufacturing processes in terms of sustainability performance measures. This approach will facilitate data exchange, sharing, and communication with other sustainable manufacturing assessment methods, such as LCA. The ease with which data can be exchanged and compared will set the stage for the development of decision-making tools capable of benchmarking sustainability performance at the process and system levels. To leverage initiatives across industry and within academia, these tools could be enabled by access to standardized repositories of reusable UMP models.

Conclusions

The goal of this study was to contrast the perspectives of industry and academic literature to identify common and contrasting challenges and deficits in enacting sustainable manufacturing theory to practice. Thus, a robust understanding of the state of the art was developed through literature reviews (narrative and systematic) on three topics: metrics and indicators, measurement science, and process modeling. To supplement literature findings, three roundtable meetings were hosted across the United States to gather meaningful input on the state of sustainable manufacturing within industry. It was found that, with limited resources available and organizational cultures that have yet to become proactive in considering the broad aspects of sustainability, companies continue to struggle to develop and implement sustainability initiatives that extend deeply into and across their operations. In part, driving research has advocated the use of many and varied metrics and indicators, without providing easy to learn introductory tools or directly equating metrics to relevant costs. In addition, industry is often reluctant to collectively share, even anonymously, information regarding processes and materials.

Synthesis of roundtable meeting results indicates there exists three strong needs. First, for process metrics that are measurable, traceable, and easy to communicate. Likewise, there is a need for these metrics and their measurement to be uniform and consistent among industries and companies. Industry faces the challenge today of comparing their sustainable assessment results to internal and external sources without the assurance that the same metric and measurement method was employed. As a result, Industry has fragmentized with some industries adopting common metrics and others simply forgoing the effort. This same need for uniformity and consistency extends to developing process models. The roundtable results indicate Industry desires one approach to process modeling that states methods to model physical and information transformations. A common process modeling approach would allow the sharing and reuse of process models in the search of superior sustainable manufacturing options. The current state of sustainable manufacturing research does not effectively support this need.

To address industries concerns requires approaches where all stakeholders have input and develop Standards for use by all stakeholders. The first standards developed for sustainability covered performing LCA, while newer standards published na and in production actively address the fragmentation within the sustainable manufacturing domain. For example, ASTM E2986 [107] assists users through selecting a goal, choosing relevant indicators, assigning process boundaries, identifying process metrics, and determining the input-output transformations to produce a good, well-formed process model. However, as research continues to uncover and address deficits, Standards development is caught in a perpetual catch-up mode. For example, composability is an ongoing area of research into modeling how UMPs meaningfully interact and link together within manufacturing systems [6], [22]. The suggestions and barriers identified in the dialogues support the reasoning that standards are needed to assist in the composition of the process models to ensure that composed models are compatible between research and industry groups. Moreover, composability is predicated on having good process information models. As of today, no Standards have been proposed to control information modeling or composing UMPs. Academic research acknowledges that standardizing information models and model composability would further the goal of integrating sustainability into manufacturing system performance decisions [158]–[160].

In addition to continuing research to better understand composability and information modeling, it is important that industry continues to be included in the discussion. A few approaches could achieve this. Proposed material for new standards could be presented to Industry participants through future roundtable meetings, or pilot projects in specific industries could serve to validate the standards and their usability, utility, and benefits. Projects would address a chosen problem within a company and attempt a solution by applying the proposed standards. Feedback would then be incorporated into revising the Standard.

Acknowledgements

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CHAPTER THREE: COMPOSABILITY OF UNIT MANUFACTURING PROCESS MODELS FOR MANUFACTURING SYSTEMS ANALYSIS

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CHAPTER 3: COMPOSABILITY OF UNIT MANUFACTURING PROCESS MODELS FOR MANUFACTURING SYSTEMS ANALYSIS

Abstract

Manufacturing accounts for 31% of all energy consumed in the United States. Of increasing concern to industry decision makers is how to make their manufacturing processes more sustainable. Current sustainable assessment methods do not consider the parameters of unit manufacturing processes (UMPs) and, thus, do not provide the granular level of modeling required for accurate sustainability performance assessment. Further, there is little research within the field of sustainable manufacturing into how to recompose UMPs to form a unified model of a manufacturing system. This research attempts to rectify this deficiency by investigating the feasibility of composing (linking) disparate processes by incorporating the workpiece as an information repository. This enables modeling the information flows between processes as a co-product of the transformations imparted to the workpiece by the selected manufacturing processes. The result is a method for assessing the sustainability performance of a manufacturing system. This method would provide value to decision makers through more capable tools to better understand the sustainability performance of their manufacturing system.

Introduction

Since its inception in the Brundtland report [4], the concept of sustainability has continued to mature as consumers become more conscious of the environmental impacts of their purchases and habits and as companies adopt environmental and social responsibility programs. The first forays of industry into sustainability involved corporate social responsibility (CSR) and life cycle assessment (LCA) programs [161]. The former targeted economic and social aspects from a policy perspective, while the latter exclusively investigated the cradle-to-grave environmental impact of products. Many of these programs were initialized with the dual objectives of improving consumer regard for the company and economizing on the reduction of energy and material costs of production. With consumer perception challenging to quantify, the focus in sustainability has been to evaluate the energy and material consumption of products during the manufacturing phase to improve cost efficiency and reduce energy-related environmental impacts (e.g., greenhouse gas emissions).

Energy consumption in the United States is predicted to continue growing [162]. Approximately 31% of energy in the United States is consumed by the industrial sector [1]. Moreover, global energy and material resource demands are predicted to increase as consumers become more affluent and global GDP grows [163]. This dictates that companies must also become more parsimonious with their resources and become more responsible for ensuring their consumption does not harm the environment or the community.

Companies have used a multitude of methodologies and indices in attempts to assess their impacts [161]. However, very few are both accurate and simple to use. While work has progressed in addressing this gap, there are still the unanswered questions of how unit manufacturing processes (UMPs) compose to form a complete manufacturing system. Composability was defined by Davis and Anderson [25] as the ability to chain different UMPs together to form a manufacturing system, wherein the UMP models can interact with one another in a meaningful manner. A UMP model explores process and material interactions, and can be used to quantify sustainability metrics. The models are used to relate material and energy inputs to outputs and can account for variations in the process. Models are developed through mechanistic relationships or empirical observation [36].

A manufacturing system contains UMPs, activities, and devices that are organized in sequence and can be interrelated. This manufacturing system will induce a transformation whereby inputs become outputs [36]. Composing UMP models enables assessing the sustainability performance of an entire manufacturing system for a selected set of representative metrics for a given product. Depending on the goal of the study, the decision maker can tailor their performance assessment to include only metrics deemed relevant.

The goal of this research is to develop and demonstrate a method for composing (linking) UMP models that enables the performance assessment of manufacturing systems. With background research acting as scaffolding, this work will assess the feasibility of composability by linking two UMPs and including material transport between the processes. This will enable modeling of how modifications to one UMP influence the performance of a subsequent UMP (e.g., removing less material in an initial milling operation increases annealing time of the workpiece). Further, composing enables the direct sustainability assessment of the finished part or assembly from product design data, initial input material conditions, and the manufacturing plan.

The next section provides background for composability research. Next, the developed method for UMP composability is reviewed and demonstrated for the case of surface treatment and coating. Finally, results of the work are discussed and opportunities for future work are presented.

Background

While the proposed method developed herein is novel, it is rooted in prior work for characterizing manufacturing processes to conduct sustainability assessments. Eastlick et al. [164] developed a method to assess the sustainability of titanium components. Their work addressed the deficit of current LCA tools in ignoring the complexities of the comprising manufacturing processes. The metrics used by his method enabled benchmarking discrete products and allowed making piecewise comparisons to aid decision making [42].

To address this deficiency in capturing UMP performance, a method was pursued that would be capable of aligning with the prevailing sustainability methods used by industry. Eastwood [98] reported a method to assess the sustainability performance of UMPs during the product design phase. His method posits that the user define a goal, identify the key manufacturing processes, identify the relevant metrics, construct models for the processes, and perform the assessment for a designed part. The method was demonstrated for comparing three gear designs to determine which had the best sustainability performance. A final assessment score was generated by summing the sustainability performance metrics of each UMP in the process flow normalized to a baseline. Garretson et al. [99] created a software tool based on this method. The utility of software tools for manufacturing process characterization was explored by Mani et al. [133], with a specific focus on manufacturing energy consumption.

The above methods required time-intensive construction of *ad hoc* models for each process and could not model the information flow between linked UMPs. In a first step towards rectifying this, Garretson [22] hypothesized that moving from *ad hoc* to generalizable models was possible by tracking workpiece characteristics, e.g., thickness and surface hardness, to model the information flow between UMPs. Information flow modeling involves tracking how inputs are transformed by the process into outputs, and mathematically ensuring that the output of one process is compatible with the input of another [133]. The model developed and deployed herein is conceptualized in Figure 10. The states of the workpiece and the process provide information to the UMP model as material physically moves from one process to another. This information is paired with the resource inputs within each UMP model to create a stream of information that can then transfer to a subsequent UPM model. At the same time, the results of that information fusion dictate the outputs of each UMP model.

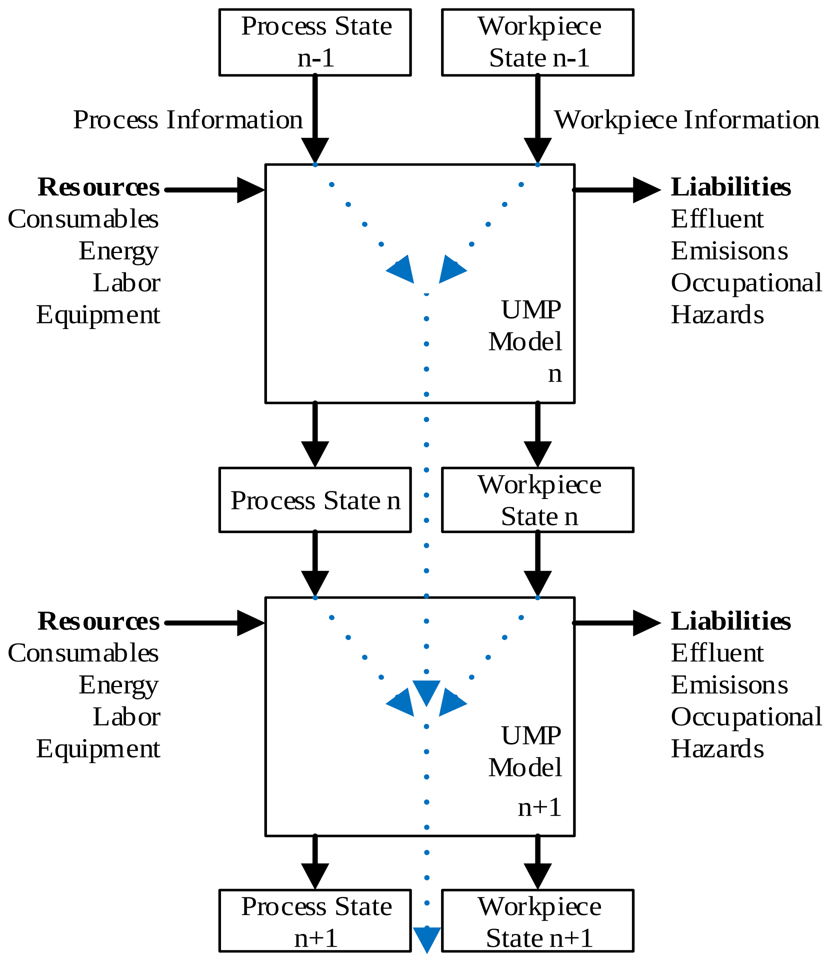

Figure 10: Conceptual composable model

Many UMP models have been reported in the literature. For example, Kellens [143] modeled a range of laser processes and Dixit [144] assessed the effect of material behavior on metal forming. Most UMP characterizations reported in the literature belong to families of processes known for their energy or material intensiveness. This prohibits comprehensive modeling of many manufacturing systems. One unreported domain is the performance of surface treatment, e.g., shot peening and spray coating. The specific goal of the demonstration herein is to model these two processes and the connecting material handling process in order to analyze the individual models and the interactions that dictate system performance. This example demonstrates how two or more composable UMP models link to create a model capable of evaluating the performance of the manufacturing system.

This following two sections describes the use. The first presents UMP modeling to support and enable the second proposed method of UMP composability. The UMP modeling section systematically presents the route through which the UMP modeling method is followed, the processes chosen for modeling, the process models, and the approach taken to incorporating UMP modeling into UMP composing. The UMP Model Composability section proceeds to investigate how each process can be composed with the others by tracking the physical and informational change of the workpiece through each process step.

UMP Modeling

The modeling method follows these steps [22]:

1. Develop Project Plan
2. Select Evaluation Criteria
3. Identify Process Plan
4. Model Process
5. Report Findings

The scope of this study is exclusive to characterizing and composing UMP models. The first step is to characterize the selected UMP (two in this case). UMP characterization, also known as process modeling, involves identifying the sub processes, boundaries, and functional units of the selected UMPs. Next, select a set of evaluation criteria. Third, a process plan is identified that is capable of describing the sub processes as they relate to the parent UMP process. Once the plan is prepared, execution involves modeling the process using literature and field sourced data to generate an inventory for all inputs and outputs. The findings of the inventory analysis are then reported.

Characterizing a UMP requires systematically modeling how each input, mechanism, and constraint interacts with the manufacturing process and the material workpiece. This can be viewed as a black box (Figure 11), wherein inputs and outputs are identified, modeled, and related to their chosen evaluation criteria. The functional unit is formulated based on the function of the process and as a unit of its output. The functional unit of a machining operation can be the quantity of material processed per unit time, as will be used in this example.

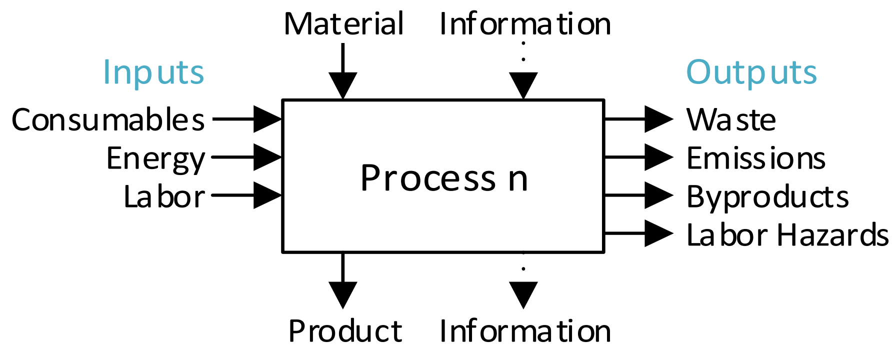

Figure 11: Unit Manufacturing process model schematic

Overview of Selected Processes

To illustrate model composability, the sequence of shot peening and coating processes is selected. Shot peening is a cold work hardening procedure used to introduce compressive residual stresses into the surface of a metal part to increase the hardness of the part and reduce crack propagation. The process itself involves firing shot, often made of rounded glass, ceramic, or metal, at a work surface with sufficient mass and acceleration to induce plastic deformation [165]. Shot peening is commonly performed on metal products prior to corrosion coating or further surface work. Shot peening was chosen because of its wide scale adoption among high performance product manufacturers and easy to model properties. There are a number of shot peening methods including:

1. Ultrasonic
2. Water-jet
3. Laser (no medium is used)
4. Centrifugal blast
5. Air blast

The shot peening process considered here is the air blast, or air nozzle, method [166]. In this method, shot is introduced into the path of pressurized air, accelerated to terminal velocity, and directed through a nozzle pointed at the work surface.

To illustrate composing models and the interaction with shot peening, the second process chosen is spray coating. There are two common forms of spray coating: dry coating and conventional liquid coating. In dry coating, a layer of dry powder is applied to a surface. The coated product is then heated until the powder flows and creates an air tight skin. In the conventional method, a solvent is added to keep the binder and filler ingredients in liquid suspension. Powder coating is heavily used by industry but requires large capital investments. Liquid spray coating, on the other hand, is widespread due to the lower barriers to entry and the versatility of the process. Here, conventional liquid spray coating is modeled. The sections below provide more background information for each chosen process.

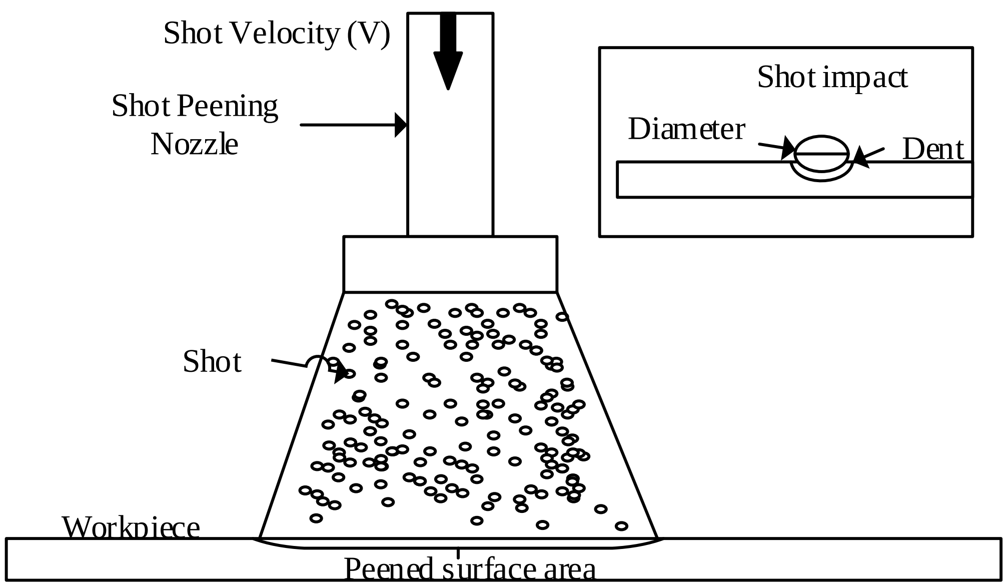

Figure 12: Shot Peening

Air Blast Shot Peening

Air blast shot peening utilizes compressed, pressurized air to accelerate shot to a predetermined velocity and funnel it through a nozzle aimed at the part surface (Fig. 12). When the shot impacts the workpiece surface, it creates an impression, or crater, that imparts a compressive residual stress to the surface [167]. The appropriate compressive residual stress is unique to the workpiece and product specifications. Once selected, the capacity to plastically deform the part to the required stress levels is dependent on properties of the process and the workpiece, e.g., process factors include shot peen geometry, material, mass, intensity, velocity, impact angle, and coverage; and workpiece factors include the material type and hardness. Workpiece properties also dictate certain process parameters. For example, selecting a high strength hardened steel workpiece dictates using an equally high strength shot, accelerated to high velocities and fired perpendicular to the workpiece surface [165].

Inspection often takes place after peening the workpiece. Using x-ray diffraction or hardness tests, inspectors construct a sub-surface residual stress profile looking for signs of overpeening [166]. If not conducted property, shot peening can actually create fatigue cracks in the surface and subsurface of the workpiece due to the exhaustion of ductility.

A peened part exhibits a characteristic dimpled texture that can be aesthetically pleasing due to its ability to refract light, creating something of a matte surface. A peened part is typically painted or coated in order to protect the workpiece from corrosion and to prolong life span.

Liquid Spray Coating

Conventional spray coating (liquid painting) utilizes liquid coating material containing paint particulates and filler and compressed air to coat a part surface. Liquid paint is fed through the body of a gun to a nozzle where the liquid is atomized by mixing with high velocity air (Fig. 13). The atomized liquid is propelled from the nozzle at high speed and contained in a radial manner by a cushioning outer layer of air [168]. The liquid layer is cured either passively (ambient temperature) or actively (in a drying oven) to form a semi permeable skin.

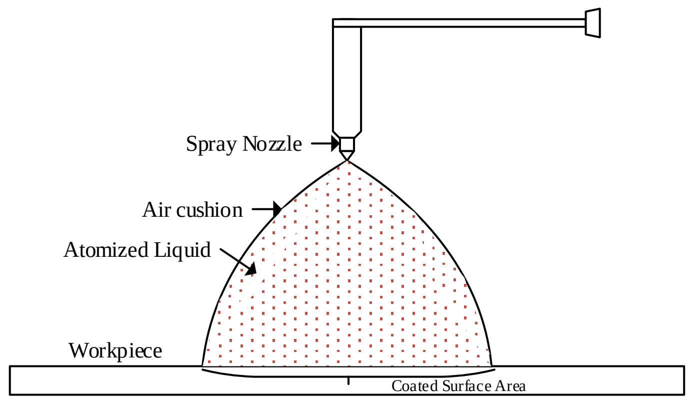

Figure 13: Spray Coating

Paint is commonly applied by hand to the work surface in bands of a certain width using a back and forth motion, while ensuring sufficient overlap for full coverage of the surface. The coating process can be repeated to increase the total paint thickness on the part surface. The amount of paint used by the process is dependent on the surface geometry and the thickness requirements. Overspray can account for a significant portion of paint use, especially for small parts. Drying time is similarly dependent on surface geometry, paint composition, layer thickness, and number of layers.

After each layer of paint dries, the surface is inspected for any signs of running or other defects, such as air bubbles or foreign material. After final inspection, the painted part leaves the paint shop and is destined either for end use by the customer or to another manufacturing process.

Process Models

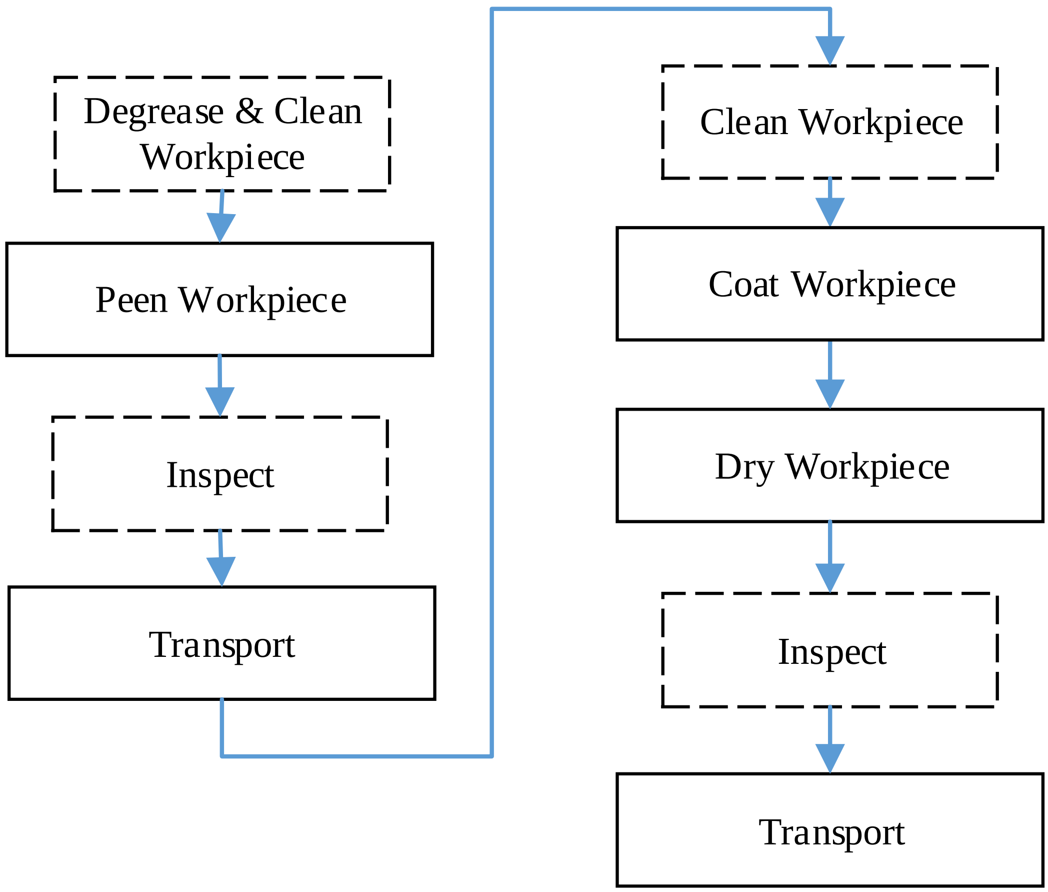

Figure 14: Manufacturing system flow

Process models were developed for shot peening, spray coating, and transportation between the processes. As mentioned above, characterization requires evaluating the transformation of inputs into outputs using a selected set of criteria. The process flows for shot peening and painting can be seen in figure 14(the dashed process steps are not modeled). This study uses criteria reflecting the three aspects of sustainability: environmental, economic, and social, to ensure performing a satisfactory assessment of the two selected processes.

It is important to note at this junction that each step in Figure 14, with the exception of transport, can be considered a UMP. Since the definition of a UMP is the smallest element in manufacturing that adds value to a workpiece through a specific transformation. While it is true that inspection and cleaning are necessary elements and value adding, it was reasoned that no inspection or cleaning can occur without a peened or coated part, thus making these ancillary processes. If was for this reason that the authors focus only on the primary processes of peening and coating.

Table 7: Evaluation criteria and general models

Aspect	Evaluation Criteria	Model Equation
Economic	Operating Cost ($)	Cop = Mcon * Ccon + ET * CE + tL * AWG
Environmental	Energy Use (kWh)	ET = ∑ Pi * ti
	Water Use (L)	VH2O = ∑ Rwat,I * Mpro,i
	GHG Emissions (kg CO2 eq.)	EMghg = Econ *(RCO2 + RCH4 * GWPCH4 + RN2O * GWPN2O)
	Total Waste (kg)	WSTT = ∑(Rland+Rinc+Rrec+Rhaz),i*Mpro,i
Social	Average Wage ($/hr)	AWG = (1/tP) ∑ Wi * tL,i
	Lost Work Days (No.)	LWD = ∑ ILLi *DLi + ∑ INJj*DLj

Table 7 lists the seven criteria and their units, alongside the model equations used to holistically evaluate the composed manufacturing system. The model equations for operating cost, energy consumption, water consumption, and total waste are unique to each process. Greenhouse gas (GHG) emissions, lost work days, and average wages are universal and are generalizable to the chosen modeled process.

GHG emissions for a process are calculated based on the energy consumed by the process and a conversion factor. While not included in this study, this factor reflects the composition of the electrical energy source. Common among LCA methods, this enables comparing the carbon footprint of manufacturing processes across different locales. Locations with a higher percentage of renewably sourced energy, whether it is solar, hydro, wind, or nuclear, will exhibit smaller footprints than other regions powered by dirty, nonrenewable sources.

The mathematical relationship for GHG emissions (Eq. 1) models the emission rates (R_i) of each pollutant for a given period of production time. It also converts the emissions rate for each pollutant to an equivalent mass of carbon dioxide using the global warming potential (GWP_i) of the pollutant. The total GHG emissions is then the sum of the products of the emission rate for each pollutant and its global warming potential, multiplied by the total energy consumed (E_T).

$$EM_{ghg} = E_{con} * \begin{pmatrix} R_{CO2} + R_{CH4} * GWP_{CH4} \\ + R_{N2O} * GWP_{N2O} \end{pmatrix} \tag{1}$$

Modeling sustainability performance is incomplete without considering the social element. The social impact model within this study considers two criteria that reflect two of the more quantifiable goals of social sustainability, i.e., the desire for a living wage, and a workplace free from danger. Modeling the first goal is done using average wage (AWG). AWG (Eq. 2) is the sum of the product of the average wage per person (W_i) and their labor time ($t_{L,i}$), divided by the total process time (t_P).

$$AWG = \left(1/t_P\right) \sum W_i * t_{L,i} \tag{2}$$

The second goal is answered using lost work days (LWD) as a measure of the safety of a UMP for its human operators. LWD aggregates the product of number of illnesses and injuries with days lost per illness (DL) and injury (INJ), respectively (Eq. 3). Alternatively, lost working days can be calculated using the probability of injury and illness occurring for each UMP (Eq. 4).

$$LWD = \sum ILL_i * DL_i + \sum INJ_j * DL_j \tag{3}$$

$$LWD = \sum P_{ILL,i} * DL_i + \sum P_{INJ,j} * DL_j \tag{4}$$

These general models are applied to the following process models in isolation and to the whole system in the following two sections.

Shot Peening

As noted above, air blast shot peening is considered herein. Quantifying the impact of peening requires tracking shot power, shot consumption, and process time. Shot power determines the energy use and cost of the operation. Shot power is an input to the shot use rate calculation, which, along with process time, becomes an input to calculating operating cost. The environmental aspect entails evaluating GHG emissions due to energy consumption by using shot power and process time as modeling inputs.

Shot power (P_{sp}) is the total power required by the process to accelerate a given mass of shot to a designated velocity. Equation 5 below is the product of shot flow rate (r_{sf}) and shot velocity (v_{sp}) divided by the efficiency (E) of the machine.

$$P_{sp} = (0.5 * r_{sf} * v_{sp}{}^2 / (3600 * 1000)) / E \tag{5}$$

Shot peening process time (t_p) is the product of coverage percentage (p_{cov}; 0-100%) and the standard batch time (t_b). Where standard batch time is the total time required to complete a single batch of product.

$$t_{shot} = p_{cov} * t_b \tag{6}$$

Shot consumption (m_{sp}) is the total mass of shot used during the peening process, and calculated as the product of shot flow rate (r_{sf}) and process time (t_{shot}).

$$m_{sp} = r_{sf} * t_{shot} \tag{7}$$

Finally, total energy consumption is equal to the product of shot power (P_{sp}) and process time.

$$E_{peen} = P_{sp} * t_{shot} \tag{8}$$

The total waste generated by the process can be calculated as the sum of waste bound for landfill, incineration, recycling, or classified as hazardous waste. The main source of material waste in shot peening stems from the inability to reuse shot between workpieces. When shot impacts the workpiece surface it can deform or crack, rendering it unsuitable for future use. However, depending on the shot material and the workpiece material, it is possible to reuse shot by inspecting the spent shot and segregating it by state. If in good condition, the shot is recycled back into the shot reservoir. Unusable shot is recycled by an external facility or disposed of in a landfill. The total waste (W_{total}) of the process is modeled in Eq. 9 as the product of shot consumption and percent of total shot that is reused (R_{shot}). It is assumed that all shot eventually will be replaced with new stock after one or more use cycles. It is also assumed that shot is measured on the basis of mass, and not on the number of units, as shot can pulverize upon impact.

$$W_{total} = m_{sp} * (1 - R_{shot}) \tag{9}$$

Spray Coating

The process model for liquid spray coating tracks the energy used to power the spray tools, the quantity of paint, and the total process time. Spray coating atomizes the liquid paint using pressurized air supplied by an air compressor. The volume of air consumed (V_a) by the process is the product of the tool airflow rate (q_s) and process time (t_{spray}).

$$V_a = q_s * t_{spray} \tag{10}$$

The total volume of paint consumed (V_p) by the process is dependent on the number of layers applied and the thickness of each layer. The equation for volume of paint consumed (Eq. 11) aggregates the total volume consumed as the product of the number of layers applied (n_l), surface area coated (a_p), and the thickness of the layers (d_t). Additionally, the model accounts for the inevitable overspray inherent in any operation by including a measure of the transfer efficiency (TE). TE is a measure of the volume of paint that adheres to the workpiece divided by the amount applied [169].

$$V_p = n_l * a_p * d_t * \frac{1}{TE} \tag{11}$$

The final energy consumption equation for spray coating is equal to the product of air consumed and the specific power of the air compressor (P_{ac})

$$E_{coating} = V_a * P_{ac} \tag{12}$$

With the paint fully dried and inspected, the part can be moved to the next downstream process or shipped to the customer. Spray coating is assumed to produce no material waste in this model. Likewise, it is assumed that no water is directly consumed by the coating process. Depending on the manufacturer, water can be commonly used in cleaning and degreasing a workpiece. The use of water for cleaning would be allocated to the cleaning step which is outside the scope of this model.

Transportation

To represent manufacturing facility operations, trucking is modeled to represent a shot peened product being palletized, forklifted into a freight truck, and shipped to the paint shop, where it is precleaned and painted. Determining total energy consumption of a truck requires modeling the time the truck is operated, distance traveled, and the fuel consumption. Here, forklift transport is not considered, since it is assumed the paint shop is located at a significantly greater distance, resulting in disproportionately higher trucking impacts.

Transport process time (t_{trans}) is calculated by dividing distance traveled (D_t) by average speed (v_a).

$$t_{trans} = D_t / v_a \tag{13}$$

Taking the product of process time, fuel consumption rate (r_{fc}), utilization ratio (R_u), and average speed gives the total volume of fuel consumption (V_{fu}).

$$V_{fu} = t_{trans} * r_{fc} * R_u * \mathrm{v}_a \tag{14}$$

The total energy consumed by the transportation process ($E_{transport}$) is equal to the product of fuel volume (V_{fu}) and fuel energy density (p_{fe}).

$$E_{transport} = \rho_{fe} * V_{fu} \tag{15}$$

With these three processes modeled, it becomes evident that there is some interaction among the three processes defined by the product design. For example, the decisions made in the shot peening stage influence the energy consumed in the spray coating process and, in turn, the evaluation criteria for the manufacturing system. Individually modeling these three unit processes sets the stage for investigating how to link the distinct models, as discussed in the following section.

UMP Model Composability

With each process fully modeled it becomes possible to link the three by physically including the transportation model and incorporating the workpiece, as previously demonstrated by Garretson [41]. Figure 15 is a flowchart of the manufacturing system illustrating how the physical flows of the workpiece occur in tandem with the information flows from process to process. In the example provided for spray coating of a peened part, the dimpling effect imparted by the shot process slightly increases the surface area of the part and the amount of paint required.

The depth of the impression is dependent on the intensity of the shot and the workpiece material. A harder workpiece with a large coefficient of restitution will absorb less energy from the impacting shot and create a smaller impression. The depth of the impression is also determined by the peening intensity and coverage. Coverage is the percentage of the workpiece impacted by shot. Intensity is a measure of the force applied to the work surface, either by increasing the kinetic energy of the shot, the process time, or both [166].

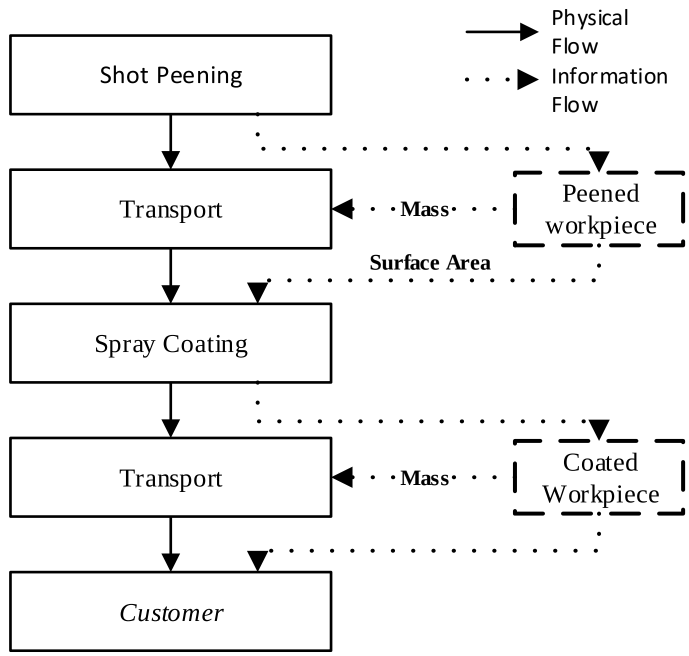

Figure 15: UMP and workpiece flow

Knowing the impression depth becomes an important test of whether coverage and intensity are meeting customer requirements. Moreover, knowing the impression depth enables calculating the final surface area of the part based on the required intensity and coverage levels. Indent depth ($h_{observed}$) depends on both the shot diameter (D) and the indent diameter (d). The SAE number is used to define shot size; the indent diameter (microns) is about equal to the SAE number [170]. Assuming the indent is circular and the shot is spherical, then the depth of the impression can be calculated after peening by using Eq. 16 [170]. Alternatively, the depth can be predicted (h_p), provided the shot velocity (v_{sp}), diameter (D), and density (ρ), along with the component Brinell hardness (B) and coefficient of restitution (e), are known This equation is quantified in Eq. 17 [170]. The derivation for this relationship was completed by Al-Hassani [171] and Al-Obaid [172].

$$h_{observed} = \frac{1}{2}\left[D - \left(D^2 - d^2\right)^{1/2}\right] \tag{16}$$

$$h_p = \mathrm{C} * D * \left(1 - e^2\right)^{1/4} * \rho_{shot}{}^{1/4} * \frac{v_{sp}{}^{1/2}}{B^{1/4}} \tag{17}$$

With the depth of the indentation known, the surface area (A_{indent}) of the indentation is (Eq. 18):

$$A_{indent} = 2\pi h_p^{\ 2} \tag{18}$$

A final calculation is needed to relate surface area and coverage. In an idealized setting and making the assumption that no shot impressions overlap, the total resulting surface area of a workpiece after peening will be the sum of the product of indent area (A_{indent}) and coverage (C) and the product of smooth workpiece area (A_{smooth}) and 1-coverage (C) (Eq. 19).

$$A_{total} = (A_{indent} * C) + (\mathrm{A}_{smooth} * (1 - C)) \tag{19}$$

Smooth workpiece area is the total area left untouched by the peening process. Coverage is measured as a percentage of total workpiece area that has been peened. However, considering that shot diameters measure in microns, it is entirely possible that a subsequent painting operation will fill the indentations with paint and create a level surface. In such a case, the volume of an indentation can be calculated as in Eq. 20 [173]. Where *d* is the diameter of the impression and *h* the depth.

$$v \ = \ (\pi / 6) * \left(3d^2 / 4 \ + \ h^2\right) * h \tag{20}$$

Looking forward, the volume of paint required to paint a workpiece to a desired thickness will increase in proportion to peening coverage and intensity. To compute the total paint consumed by the spray coating process, combine Eq. 19 with Eq. 11 by substituting A_{total} from Eq. 19 for a_p in Eq. 11.

$$V_p \ = \ n_l * \mathrm{A}_{total} * d_t \tag{21}$$

At this point, recalculating the total energy consumed by the process using Eq. 21 will reflect not only the parameters of the spray coating process, but also the decisions made in the peening process. Hong [174] reported that increasing shot diameter increased the plastic deformation of the workpiece surface by creating a larger volume impression, thereby reducing the number of shots required. However, as understood by linking these two processes, the increased shot diameter may save time during the peening process at the expense of increasing the volume of paint required to achieve a desired paint thickness.

Understanding how two processes link creates a situation where informed decisions can increase the sustainability of an entire manufacturing system. The total power consumed by shot peening comes from the shot flow rate, shot velocity, and process time. All three reflect the customer's requirement for a specified intensity and coverage level. Similarly, spray coating energy consumption reflects paint volume and process time.

In contrast, the energy costs of transportation arise from mass (size, density) of the workpiece material. Transportation can be linked with shot peening and spray coating by accounting for the change in mass or volume of the workpiece by the UMP. Shot peening is a surface integrity process and removes no material and imparts no appreciable change in mass or volume. With spray coating, mass and volume will increase in proportion with the amount of paint applied. Depending on the type of coating, typical densities range from 790 to 1260 kg/m^3 [175]. Therefore, depending on the final thickness of the deposited paint layer, the mass of the workpiece will increase after the spray coating process. This increase in workpiece mass influences the transportation sustainability performance.

Transporting the workpiece from peening to painting, and from painting to the next process can be modeled using the mass of the workpiece. In transportation, trucks are rated on their ability to carry a given weight (e.g., a ½ ton rated truck can carry ½ ton of material). Therefore, as the mass of the workpiece increases due to coating, the impact per part (e.g., energy use and related emissions) increases. The sum of all workpiece masses (m_{part}) is equal to the total freight weight (M_{fr}), as shown below (Eqs. 22-24).

$$M_{fr} = \sum_{i}^{n} m_{part_i} \tag{22}$$

where

$$m_{part} = m_{workpiece} + m_{coating} \tag{23}$$

and

$$m_{coating} = V_p * \rho_{coating} \tag{24}$$

with the constraint that the total freight mass (M_{fr}) cannot exceed the rated mass capacity ($M_{capacity}$) of the truck (Eq. 25).

$$M_{fr} \leq M_{capacity} \tag{25}$$

Due to the complex interplay of engine efficiency, vehicle mass, and resistance to motion, an empty truck has roughly the same fuel economy as when loaded. Optimizing fuel consumption and reducing transportation costs is a matter of achieving high utilization rate (R_u), which is the ratio of freight weight to truck capacity. The utilization ratio is an input to the fuel consumption calculation (Eq. 14). Adding mass reduces the number of workpieces that can be transported for a given truck. As a result, the unit cost of transport per workpiece increases. Moreover, from a sustainability context, fewer workpieces per shipment results in an increased emissions rate per workpiece.

Assessing the Manufacturing System

With the process models now calculated, the entire manufacturing system can be assessed using the seven evaluation criteria mentioned earlier. These seven evaluation criteria can be visualized as an IDEF0 model (Appendix A). In this visualization, the controls and mechanisms (the top down and bottom up arrows) dictate how the inputs (left-side) transform into the outputs (right-side). IDEF0 modeling allows incorporating the critical process parameter set in shot peening, spray coating, and transportation as controls within this system boundary to show their influence in shaping the output results. An IDEF0 visualization succinctly illustrates how the critical elements of decomposed systems identified through UMP characterization can be reassembled to create composable system models. The IDEF0 model combines the concepts from the figures above with criteria from Table 7 to produce a holistic visualization capable of elucidating to a decision maker how linking models with sustainability criteria will enable sustainability assessment of a manufacturing system.

Assessing the energy use for the entire system is calculated by summing energy consumed by shot peening, spray coating, and transport (Eq. 26).

$$E_{Total} = E_{shot} + E_{coating} + E_{transport} \tag{26}$$

The next measure is operating cost (Eq. 27). Operating cost is a powerful criterion for measuring the sustainability of a process for the simple reason that it is familiar to C-suite decision makers. Thus, if a more sustainable system has a lower operating cost, it will surely be chosen over other less satisfying options. The operating cost of the system aggregates the total material and resources consumed, the use rate, and the cost for each. Total operating cost is the aggregate of the product of the volume of paint (V_p) and cost of paint (c_p), the volume of shot consumed (m_{sp}) and cost of shot, the freight cost (c_f) and distance traveled (D_t), the total energy consumed (E_{Total}) and cost of energy (c_E), and the sum of labor costs (c_{labor}) for each process (Eq. 27).

$$\begin{aligned} C_{op} = {} & (c_{sp} * m_{sp}) + (V_p * c_p) + (c_F * R_u * D_t) \\ & + (E_{total} * c_E) + \sum (c_{Labor_i} * t_{p_i}) \end{aligned} \tag{27}$$

With the energy and operating cost calculated, the next step is to calculate the environmental and social impacts of the system. For example, total energy consumption would be used to calculate the system-level GHG emissions. Total system waste is the sum of wastes produced by each process, though in this example only shot peening produces waste The social assessment involves determining the relative risks of operating each process to the operators. Thus, the total social impact is the sum of the incidents for each constituent process.

Discussion

Unit manufacturing process modeling was undertaken to characterize shot peening, spray coating, and trucking. Characterizing these processes increased the detail of the resulting sustainability assessments. The need for this work was highlighted by the lack of consideration of common LCA methods for the impact UMP parameters on the full manufacturing system. Shot peening and spray coating were characterized to demonstrate the modeling of surface integrity processes. It was demonstrated that parameters chosen in shot peening influence the volume of paint consumed, the mass of the final part, and the transportation between processes.

The information flows among the process models highlight an interesting characteristic of composability. The parameters dictated by customer requirements, such as coverage and intensity, cannot change. This leaves only a few free parameters for the manufacturer. Thus, customer design requirements influence the selection of manufacturing processes. A requirement that the workpiece be cold hardened precludes the use of induction hardening or tempering. Likewise, a cost constraint may preclude designers from selecting powder coating, due to its higher fixed costs and limited material compatibility. In addition, processes come with their own requirements and characteristics; for example, painting and shot peening dictate that the workpiece be cleaned and free of any contamination. In short, design requirements dictate which process is selected, but the unique characteristics of the chosen processes drive the characterization and assessment of the manufacturing system.

It has been postulated that the characteristics of the process influence the assessment of the manufacturing system. Considering a more granular investigation, the characteristics of the workpiece (e.g., material type and condition) can have two effects. First, they influence the order in which processes are performed. Second, they influence the parameter settings for the chosen processes. Tracking the state of the workpiece increases the accuracy of UMP modeling by enabling UMPs to be linked in a manner such that information flows are preserved. This increases the accuracy of sustainability assessment for the entire manufacturing system, and eliminates the risk of sub optimization occurring.

As demonstrated in this research, modeling the workpiece requires tracking specific details related to the workpiece, such as part geometry and material microstructure. Incorporating the workpiece enables information to transfer from process to process with the workpiece acting as an information repository. The repository is then accessed by modeling the workpiece's geometry and microstructure interacting with the processes.

Future work within this field will focus on validating the models herein described, and developing a set of composable system models encompassing all process parameters. In this way, the linking of UMP models can be effectively and efficiently performed on a macro scale, improving the accuracy of sustainable assessment of manufacturing systems.

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CHAPTER FOUR: AN INFORMATION MODELING FRAMEWORK FOR SUSTAINABLE MANUFACTURING UNIT PROCESS COMPOSABILITY AND SYSTEMS ASSESSMENT

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CHAPTER 4: AN INFORMATION MODELING FRAMEWORK FOR SUSTAINABLE MANUFACTURING UNIT PROCESS COMPOSABILITY AND SYSTEMS ASSESSMENT

Abstract

Characterizing unit manufacturing processes (UMPs) within manufacturing systems can advance the goals of sustainable manufacturing by identifying waste streams, energy consuming actions, and other evaluation metrics. This information is identified by constructing models of UMPs and assessing their performance with respect to design criteria. Assessing the performance of a manufacturing system consisting of multiple UMPs requires composing, or linking, each individual UMP model while also preserving information flows. This can be accomplished with a composing model that characterizes the transformation of a model output variable for one UMP to an input variable for the model of a subsequent UMP in the process flow. Methods have been proposed to aid in characterizing and composing UMPs for sustainability performance assessment, however, none have been reported that do so in a complete manner. Currently, no information modeling framework exists that specifies how to collect, label, and transmit data to preserve information flow, nor to promote reusable and sharable UMP models and system models of composed UMPs. A framework is presented for constructing UMP information models and composed UMP-based manufacturing systems for use in sustainability performance assessments. The framework borrows techniques from the computer science domain to model the flows of information at different abstractions to holistically capture multiple layers of information. The framework led to the development of an XML Schema to capture and label information in a reusable, sharable manner. The Schema structures the information flows within a system as a series of elements and attributes, with the end result a format for engineers to follow in modeling the information flows within a composed manufacturing system. Future work will implement this framework in a desktop application to expedite the composing of manufacturing systems and conducting sustainability performance assessments.

Keywords

Composability, Information Modeling, Unit Manufacturing Process. Manufacturing System

Introduction

Sustainability has seen extensive research since its written genesis in the Brundtland commission report [4]. Subsequently, environmental sustainability was enacted in methods and tools to reduce the life cycle environmental footprint of a product (e.g., life cycle assessment). With time, the lens of sustainability was progressively applied to different phases of a product, and its supporting activities. In particular, the manufacturing phase of the product life cycle has seen strong activity in investigating improvement of sustainability performance of machines, processes, and systems [46], [176]. During the manufacturing phase, value is added to the product. Sustainability performance can be effectively addressed by examining and modifying these value-added processes. The manufacturing phase is complex, however, with many issues to be addressed for sustainability to become operationalized and codified within manufacturing operations [14]. Methods and tools have been developed to assess various sustainability performance metrics of machines, processes, systems, and factories [47], [177], [178] , however, the main limitation to the current methods and tools is their *ad hoc* characterization which leads to issues of incompatibility and extensibility. This *ad hoc* characterization of manufacturing processes and systems has resulted in information wastes as process models developed by one research effort cannot be easily integrated with those from other efforts. The information complexity of different assessment methods and unit manufacturing processes (UMPs), further inhibits the linking of processes within models of manufacturing systems. One possible solution is to develop process-oriented, composable information models built upon standardized process characterization methods. An information model captures the concepts and relationships of a chosen domain. Further, it is an organized information structure that can be implemented in software to store, process, and analyze domain data [137]. These information models could conceivably structure incoming information for one process in a manner enabling its export to a receiving process without information loss or added noise. A resulting sustainability assessment method could then be used to record the transfer of information between models of different UMPs, and to calculate the sustainability performance for each UMP in a manufacturing process flow based on the chosen metrics and input data and underpinning models.

Information modeling originated in software engineering for modeling system structures [179]. From software engineering, information modeling migrated to civil and construction engineering, where it was adopted to construct building information models to digitally represent the physical and functional characteristics of a building [180]. Only within the past 15 years has information modeling been applied in the domain of manufacturing. Within manufacturing, information models have been developed to control product information (e.g., geometry, feature, and assembly knowledge) [181], [182]. The National Institute of Standards and Technology (NIST) is active in the field of information modeling, having published a product information modeling framework for product life cycle management [183] which was extended to a generic, abstract tool [184]. Information modeling of disassembly processes has also seen recent interest [185]. While product and process information models have been researched and have begun to be standardized, a deficit remains in understanding the composability of process models and the information flows between processes. No manufacturing information models have been reported, with the exception of Zhang et al. [137], that incorporate sustainability assessment. Additionally, most information models have been reported in conceptual form, and only a few (e.g., CPM and CPM2) have become implemented in software applications.

The objective of this work is to develop and demonstrate a framework for information modeling that will facilitate the composing of manufacturing processes for sustainable systems assessment. This framework will assist in efforts to develop sustainable manufacturing methods and tools capable of being standardized for industry use. As a result of the work presented below, a three-layered framework was developed. First, IDEF0 is used to abstract the manufacturing system to show information flows between selected indicators. Next, SysML is used to describe a design-oriented application, and, third, XML Schema is used to structure the required data for the application. The framework identifies how to structure the required data, model the composed processes, input the structured data into the model, and assess the sustainability performance. The information framework is demonstrated by modeling a representative composed manufacturing system, consisting of tempering followed by shot peening.

Literature Review

Before presenting the proposed composable information modeling framework, a brief literature review on information modeling, UMP modeling and composability, and sustainability assessment is presented.

Information Modeling

An information model defines different concepts, relationships, constraints, rules, and operations to structure data semantics within a given domain [26]. In this manner, concepts and their relationships are semantically defined. Information models structure and organize data in such a way that it can be shared and reused. Traditionally, the strength of information models lies in their ability to visualize high level abstractions of information. This allows for greater conceptual understanding of information flows [137]. Furthermore, this abstraction makes information models independent from the physical methods for information transfer [185]. Thus strengthening the ability for information models to be reused and shared.

Lee [26] summarized multiple information modeling techniques, such as Entity-Relationship modeling (ER), functional modeling, and object-oriented modeling (OO). ER modeling focus on data and relationships between databases. Functional modeling decomposes system functions into their respective actions, processes, and operations. IDEF0 is an example functional modeling approach [186]. OO modeling is an approach to modeling concepts, their relationships and attributes, for software implementation. In OO modeling, concepts are conceived as being independent objects that share some, all, or no attributes with others, but instead can inherit or pass on attributes to other objects within their relationship web. Within the OO paradigm, unified modeling language (UML) is a common standard for visualizing software design [187]. UML and its extensions, Systems Modeling language (SysML) [188] and extensible markup language (XML) [189] provide the ability to conceptualize and enact information models. UML has been notably implemented in NIST's Core Product Model (CPM). The model uses UML to capture engineering information generated during product development. NIST also developed another model called the "Open Assembly Model" (OAM) which extends CPM to include the function, form, and behavior of the assembly. OAM also defined a system level conceptual model, likewise using UML as its chosen modeling language. More recently NIST has investigated the feasibility of developing domain specific XML schema for manufacturing processes with MatML an XML schema developed for materials information exchange [190], acting as inspiration. XML is an extensible meta-language that can be customized to fit a domain-specific language. XML uses semantic tags within a document to assist with document storage and exchange. In effect, XML and their schemas (rules) make data sets self-describing. A domain specific XML provides a medium for communication between users [191]. SysML is a more recent language adopted by OMG. In 2006, OMG published the first standard for SysML to support systems engineering and systems modeling. SysML is a graphical language for modeling large-scale, complex, multi user and multi-disciplinary systems [192]. SysML was developed to fill a fundamental gap left by previous modeling languages such as UML and IDEF concerning the exclusion of parametrics and engineering analysis. Prior to SysML non-standardized analysis methods were often disjoint from the system architectural models [193].

To date, most information models proposed for use in the manufacturing domain have disregarded sustainable manufacturing related information and information modeling. These information models (CPM, CPM2, OAM, Disassembly information model) focused on the conceptual, abstract construction of information models. Moreover, none describe efforts to develop granular graphical representations of information models implemented in software applications.

<u>Sustainability Assessment</u>

Sustainability is widely seen as encompassing three aspects: economic, environmental, and social. Assessing sustainability requires methods and tools capable of identifying for a given process, what metrics should be used, how measurements should be taken, how metrics should be weighted, and how to present the final assessment results. Each aspect of sustainability first requires metrics and indicators capable of synthesizing process and product information for assessing overall sustainability. Many metrics and parent indicators have been proposed in the literature. In one recent study 2555 [108] unique metrics were identified. Despite the astounding number available, most metrics and indicators continue to represent environmental impact [31]. Once a metric and indicator set are chosen, the second challenge facing manufacturers is to select an evaluation method.

Many evaluation methods have been proposed for assessing process sustainability. General frameworks include the unit process life cycle inventory approach UPLCI [103] and the recently standardized UMP assessment method [18]. However, comprehensive frameworks such as these still leave estimation or measurement method open. Duflou et al. [194] in a review of six manufacturing processes classified the evaluation methods as being theoretical, screening, or in-depth (empirical). Screening has fallen out of favor due to its inaccuracy, though the other two methods continue to see strong research. Munoz and Sheng [115] theoretically investigated the environmental impact of machining processes. Gutowski et al. did the same in [195], investigating from a thermodynamic perspective the resource consumption of manufacturing processes. Gutowski et al. also empirically investigated the energy requirements for a number of manufacturing process [116], with turning operations gaining specific attention by Li and Kara [117]. The approach utilized within this study follows the approach proposed by Eastwood and Haapala [98]. Eleven metrics are preselected, and the methodology follows the ASME standard for UMP modeling and sustainability assessment.

<u>UMP Modeling and Composition</u>

A UMP is the smallest element of manufacturing where value is added through a transformation to a workpiece. More than one machine may constitute a UMP so long as the machine’s purpose can be traced back to one value adding activity. UMP models are developed to explore process and material interactions, and can be used to quantify sustainability metrics. The models, developed through mechanistic relationships or empirical observations, relate material and energy inputs to outputs [42]. A process model links the internal transformation of inputs to outputs to the evaluation metrics selected for final performance evaluation [36]. Evaluating the model themselves and the results produced provides potential for discovering opportunities for improvements. Many UMP models have been reported in the literature. For example, Kellens [143] modeled a range of laser processes and Dixit [144] assessed the effect of material behavior on metal forming. Once a UMP has been characterized and modeled, it can then be composed (linked) with other UMPs to produce linked chains comprising manufacturing systems. Like information modeling, composability as a concept originated in the software domain. Davis and Anderson reported that composability is the meaningful linking of components with the ability to combine and recombine components in different systems for different purposes [25]. Further, composability requires understanding the inputs, outputs and constraints of the constituent processes. To integrate them, the inputs and outputs must match, and the functional purpose of each process must be sensible [160]. However, composability research remains conceptual (e.g. [160], [196]) with little reporting on the challenges in implementing and utilizing composed models. Only recently with Garretson [22] and Smullin et al. [197] have UMPs been mathematically composed. This is important as mathematical composition is a necessary precursor to information modeling and for use software implementation.

The methods proposed in the literature for measuring the sustainability of a process require thorough understanding of manufacturing processes. Additionally, the sustainability of a process is dependent on the workpiece involved, thus a thorough understanding is also required of material properties. The level of knowledge required results in few companies modeling their processes. Those that do model follow different tacit approaches that lead to incompatible models, incapable of composing. Additionally, the different methods and approaches stymies software programs from properly organizing and manipulating the available information. Therefore, needed is a framework capable of codifying UMP and sustainability information for inclusion in standards development. In this paper, a multi-level composable information modeling framework is presented and demonstrated with the aid of a custom designed desktop application for manufacturing systems sustainability assessment. The vision of this framework is to provide a foundation upon which a standard may be developed to accompany current standards on process characterization for sustainability assessment by specifying the means in which to characterize processes for composability.

Standards Review

This section presents the current standards capable of addressing process characterization for sustainability assessment but not process composability. Existing manufacturing standards provide instructions for designers, engineers, builders, operators and decision makers to conduct activities within their fields. They also facilitate communication between stakeholders across different organizational borders. Furthermore, standards facilitate information transfer across borders of the manufacturing system hierarchy and between life cycle phases. Standards are fundamental to advanced manufacturing systems to facilitate the efficient delivery of information. Standardization enables automating system responses and permits establishing repeatable processes all sharing common functional understanding. This reduces the cost of adopting new technology.

To this end, ASTM International has formed both a committee on Sustainability (E60) and a Subcommittee on Sustainable Manufacturing (E60.13) [157]. Of immediate relevance to the work presented in this paper is E3012-16 Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes, which provides guidance for the actual characterization of manufacturing processes [198]. This guide outlines a characterization methodology and proposes a generic representation from which manufacturers can derive specific UMP representations for meaningful sustainability performance analysis. Also, ASTM published two related standards namely, E2986-15 Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes, which provides guidance for manufacturers on how to conduct a sustainability study in order to improve their practices [107] and E2987/E2987M-16 Standard Terminology for Sustainable Manufacturing, includes terminology applicable to sustainable manufacturing [199].

The vision of these standards is to provide manufacturers with a way to better describe their manufacturing processes with regards to sustainability. This will facilitate data exchange, sharing and communication with other manufacturing applications, such as LCA. The ease with which data can be exchanged and compared sets the stage for the development of decision-making tools capable of comparing alternative composed manufacturing systems. These tools would access standardized repositories of reusable UMP models for sustainability assessment. Such a repository does not yet exist.

Information Modeling Framework for Composing Manufacturing Processes

The development of UMP model repositories has been challenged by the in-depth nature of model development (e.g., time and data availability) and a lack of a standard representation to facilitate model sharing (e.g., generalizability, validation, and accepted sustainability metrics\indicators). To address these challenges, an information modeling framework has been developed (Figure 16). The framework consists of three parts: (1) an abstract, functional representation of the UMP information flows and sustainability performance metrics to aid in manufacturing process assessment; (2) a mechanism for the holistic capture of systemic information flows and interrelationships to facilitate manufacturing process composability; and (3) a mechanism to structure and label UMP and UMP-linking information to aid in manufacturing systems assessment.

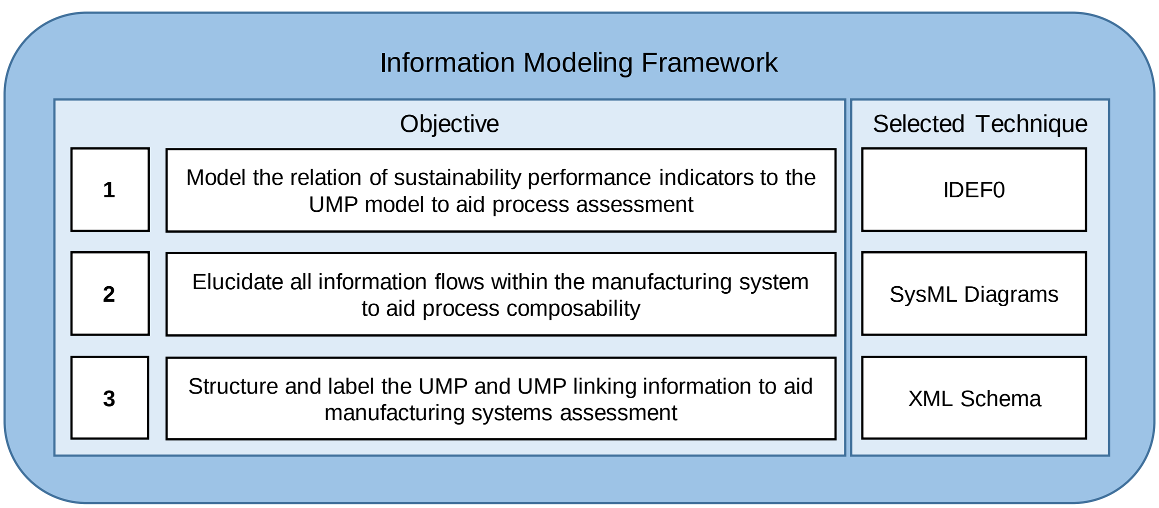

Figure 16: Layers of the Proposed Information Modeling Framework

The literature offers approaches to developing information frameworks. One such approach is the Zachman framework [200], which is used in this research to understand the requirements to satisfy each objective in the information modeling framework. The Zachman Approach Section presents the Zachman framework and its application in this research. Following is a representative manufacturing system covered by the information modeling framework. The later sections investigate meeting the objectives of the information framework through functional and graphical representations of the information flows within a manufacturing system and development of an architecture to structure and label information to aid manufacturing systems assessment.

Zachman Approach

The Zachman approach is a design framework for enterprise architecture [134]. It breaks down an enterprise design concern into six discrete sub-problems. Each sub-problem answers one cognitive primitive along a six celled horizontal scale of primitives. For each sub-problem the framework asks six cognitive primitives: What, How, Where, Who, When, and Why. Table 8 presents the Zachman framework as first proposed in [200]. The Zachman framework allows taking a holistic, thorough view of the problem at hand, while remaining grounded through the careful separation of sub problems. Narayanan et al. believed this framework to be ideal for the creation of information modeling standards. The researchers later realized the Zachman framework's ability to identify gaps and overlaps in standards development [201] and were able to elucidate the relationships between table cells in [136]. The goal of each development was to gain a better understanding of how to integrate product and life cycle information models, though once again, a gap was noted to exist in modeling the interaction between process models.

Table 8: Zachman Framework

	Data What	Function How	Network Where	People Who	Time When	Motivation Why
Objective/Scope (contextual)						
Enterprise Model (conceptual)						

System Model (logical)	
Technology Model (physical)	
Detailed Representation	
Functioning Enterprise	

To become sustainable requires meeting increasing stringent internal and externally mandated goals. For example, regulations restricting the use of heavy metals or noxious pollutants can have drastic effects on manufacturing processes. Considering that manufacturing processes and constituent machines are many and vary, compliance with regulations can be challenging. The Zachman framework helps to break down the information modeling challenge into manageable sub problems to ensure that regardless of machine or process type, an information model has been developed capable of assisting that process achieve sustainability.

Using the Zachman framework as the guide, the research conducted herein proposed meeting each of the six sub problems using IDEF0, SysML, and XML as modeling languages where the scope is set to a predetermined set of sustainable metrics source from Eastwood et al. [98]. The culmination of the Zachman framework (row 6) is a realized tool demonstration. Table 9 visually presents this approach.

Table 9: Proposed information modeling framework using the Zachman Framework as scaffolding

Zachman Framework Row	**Information Modeling Technique or Language**
Scope	Table of Selected Metrics and Equations
Concept	IDEF0
Logical Architecture	SysML
Technical Architecture	SysML
Date Representation	XML Schema
Functional Entity	Tool Demonstration

Representative Manufacturing System

Products rarely require only one UMP. In most cases a finished product will be worked upon by more than one UMP. To demonstrate this, six UMPs and transport were composed to generate a manufacturing system. In order to eliminate a priori knowledge of systems and maintain impartiality, the modeled system is conceptual, and is not rooted in any industry operations. Parts of this system were modeled previously in [35] and [36]. Figure 17 illustrates the combined system. Solid boxes are UMP, while the dashed boxes indicate the workpiece state between processes. Arrows indicate the key variable outputted by the previous process and inputted into the next. There can be more than one possible variable, it is up to the user to determine which variable most significantly influences process performance. Combined, this system demonstrates the diversity and ensuing complexity present in composability. For example, there are multiple categories of processes present in this system. Reducing is a MRR process, Annealing, Through Hardening, and Tempering are property modification, and peening and spray coating are surface modification and surface finishing category processes respectively. Likewise, the diversity of linking variables is evident. Linking variables can either represent workpiece material property (UTS, Yield Strength) or geometry modification (Thickness, Surface Area) or can be hybrids (Mass) (Figure 18). Additionally, this model presents concepts such as forward and backward process constraints. Following the work of Garretson [35], Tempering is forwards constrained; it can only follow Through Hardening. The diversity of processes and variables was addressed in the Schema, likewise for the process constraints.

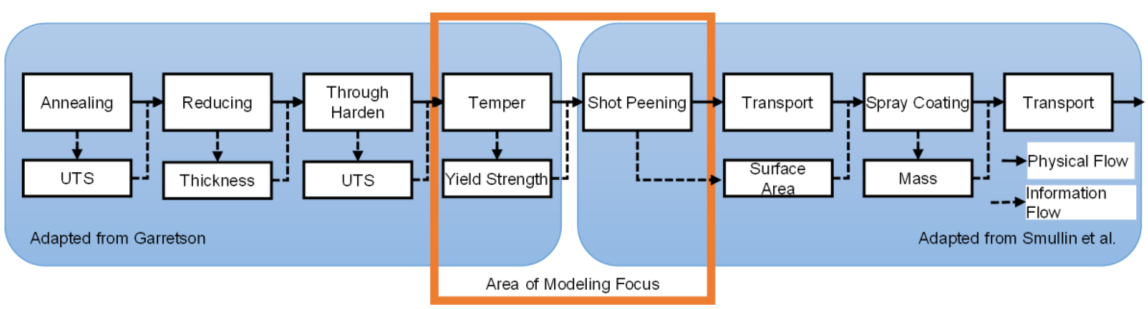

Figure 17: Combined manufacturing system

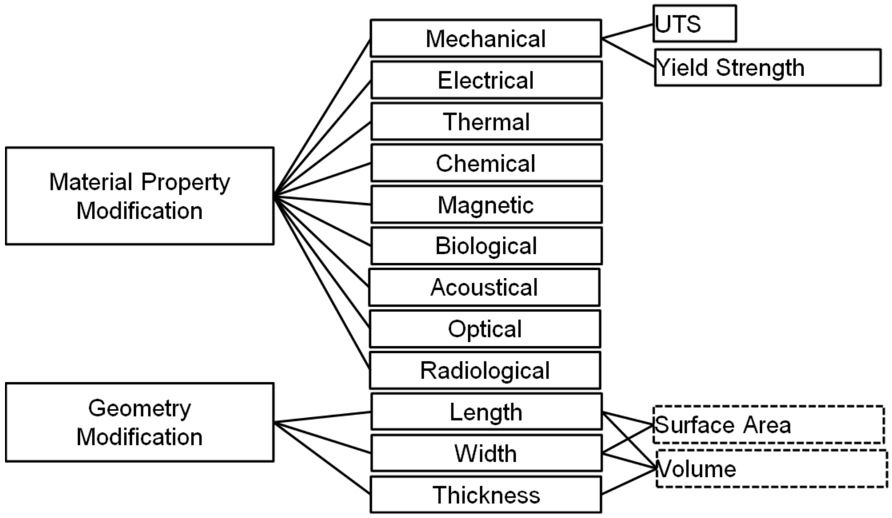

Figure 18: Diversity of linking variables

The linkages between States 1 through 4 were modeled by Garretson [22] and States 5 and 6 by Smullin et al. [197]. However, the linkage between Tempering and Shot Peening is presented here as a brief demonstration of composability in practice. In shot peening, there are three decision parameters that must be set prior to undergoing operations. A customer must choose the peening media, intensity, and coverage. Choosing a media depends largely on the workpiece material. The workpiece in question is a steel alloy (SAE 4340) which typically is peened using ferritic materials (cast iron, cast steel). Intensity is set based using Almen strips and incorporates a number of factors – type of material, type of loading, component thickness – that makes setting a precise limit very difficult. Coverage is a percentage measure of the workpiece surface that the customer wishes peened. Davis [165] developed a mathematical model that incorporates yield strength of the workpiece to determine the coverage needed to produce a desired compressive strength.

Tempering and Shot Peening can now be composed by virtue of Equation 28. The yield strength of the workpiece after tempering is inputted into Equation 28 to receive a total coverage value.

$$Z = 100\left[1 - \exp\left(\frac{-3\beta 0.05 m C_d PD(\sin\theta)^2}{2.5\rho_s(\tan\alpha)s_d^{\ 2} YS\pi a^2}\right)\right] \tag{28}$$

In Equation 28, C is coverage, β is a constant set equal to .2 [202], P is pressure, D is the nozzle length, ρ is the shot density, Y is the yield strength of the workpiece, E is the modulus of elasticity of the workpiece, d is the standoff distance, α is divergence angle of the shot stream, a is the indentation radius and m is the mass flow rate. D depends on the class of shot chosen. With coverage known, process time can be estimated. The time it takes to peen the workpiece to the required level depends on the coverage factor, K, of the shot stream, K_{avg} is calculated in Equation 29 [203]:

$$K_{avg} = FR * \mathrm{A}_{impact}\left(\frac{(2\sqrt{Z}/\pi)}{M_{shot}Z(\mathrm{t}_{trans} * (2\sqrt{Z}/\pi)}\right) \tag{29}$$

Where FR is a constant set to 1 A_i surface area of the part, M_{shot} is the mass of the part, and N is the rate of dent creation per unit area. N is a constant set prior to operation. Then, with K known, the time to achieve a given coverage can be determined by solving for time Z_t in equation 30, and then process time in Equation 31:

$$Z_t = \frac{\ln(1-C/100)}{-K_{avg}} \tag{30}$$

$$T_{process} = A_{surface} / \mathrm{Z}_t \tag{31}$$

With process time determined, the shot peening process model is run and incorporates this new value. Once the model is run, then the process is assessed on its social sustainability performance using equations from Table 7. For brevity, this portion of the math calculation is not shown. Instead the results are shown in Chapter 5 where the entire system is assessed using the software application.

Functional Representation

The first two rows of the Zachman framework cover both technical and administrative tasks. As noted by Narayanan et al., [134], IDEF0 is particularly well suited to represent row two as it provides overall system level knowledge [204]. IDEF0 (integrated definition 0) is a member language of the IDEF suite of descriptive modeling techniques. IDEF0 is a functional graphing language capable of graphically representing a functional system as a set of activities and actions. IDEF0 models consist of a hierarchy of cascading, interlinked diagrams with defined names. Metrics are presented as boxes. Arrows attached to the boxes indicate the interaction between boxes. In this visualization, the controls and mechanisms (the top down and bottom up arrows) dictate how the inputs (left-side) transform into the outputs (right-side). At the highest level, an IDEF0 diagram represents the entire system. This diagram is progressively broken down into ever more detailed representations until activities are exhausted or the necessary level of detail is obtained. The IDEF0 model in Appendix A describes the top level sustainability metrics and the information flows between in a representative manufacturing process, in this case, shot peening [197]. The IDEF0 allows visualizing the information flows and their origins as they impact the metrics. The mappings between processes and performance metrics facilitates identifying processes relevant to metrics and vice versa [205]. This high level abstraction of the information flows between manufacturing actions and sustainability metrics elucidates the connections that must be addressed in greater detail to fully understand how an information model could be realized in software form. This requires addressing rows three and four in the Zachman framework using a secondary modeling language.

<u>Graphical Representation</u>

The third and fourth rows of the Zachman framework concern the systems and technical aspects of an enterprise. It is only fitting then that a systems modeling language (SysML) be used. Not only is SysML capable of modeling a systems perspective, it is also robust enough to delve into technics modeling including user requirements modeling [206] and parametric modeling [192] without compromising its holistic qualities. SysML reuses parts of UML, and adds new functionalities specifically intended to aid systems engineering [192]. Figure 19 summarizes the functions of SysML as taken from [188]. As shown there are three subsets to SysML: behavior diagrams, requirement diagrams, and structure diagrams. New to SysML from UML was the addition or modification of diagrams: activity, requirements, block definition, internal block, and parametric. Each top level diagram and its children focus on graphically modeling different aspects of a system. Behavior diagrams are more focused on software/hardware workflow and user interaction. Requirement diagrams enable explicit mapping of user requirements to system functionalities. With the benefit that conflicting or insurmountable requirements can be identified earlier in the design phase. Structure diagrams define a system as blocks. Blocks in SysML are defined as “modular units of a system description, which define a collection of features to describe a system or other elements of interest. These may include both structural and behavioral features, such as properties and operations, to represent the state of the system and behavior that the system may exhibit” [188]. The block definition diagram is similar to an ER diagram. The internal block diagram provides granular level detail on the relationships between blocks (processes). The parametric diagram is used to capture the equations involved in calculating one or more attributes of a block, including the information transformation within and between blocks.

While each diagram can be applied to a system, there are recommendations and best practices within the literature as to where to start, and which diagrams to use based on the system’s characteristics. For example, Wolkle and Sheal utilized Structure diagrams, while Huang et al. did as well for modeling phases of the product lifecycle development[192], [207]. Soares et al. investigated using requirements diagrams to better connect user requirements to end product results [206]. Moreover, Friedenthal et al. recommend a starter set of six diagrams, called SysML-Lite by the authors, for their ability to robustly but succinctly cover all systems [208]. Figure 20 represents these six diagrams. These six diagrams were chosen to model composability based on the recommendations of Friedenthal et al. and the supportive findings of the literature.

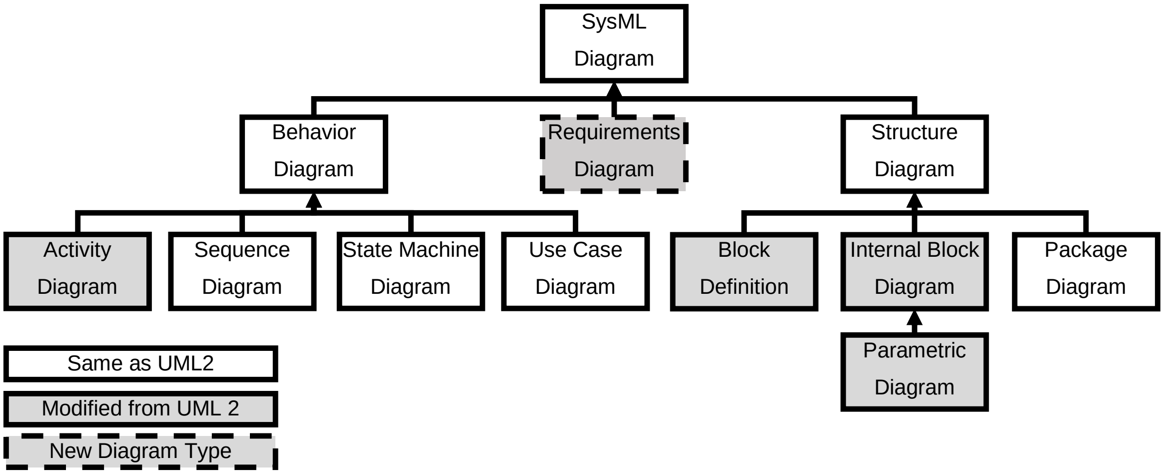

Figure 19: Overview of all SysML diagrams

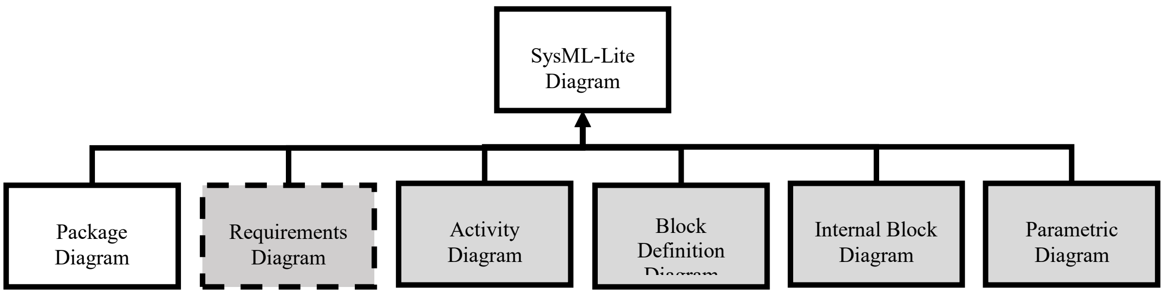

Figure 20: Overview of the six chosen SysML diagrams

Package Diagram

The package diagram was first diagram used to model a sustainable composed system (figure 21). The package diagram very simply illustrates within what "folders" the blocks of the system will reside. Thus, there are four folders representing the four elements of the Composed System. The Requirements folder will hold requirements covering the need for processes to be assessable, and the need for processes to be compatible based on a number of constraints.

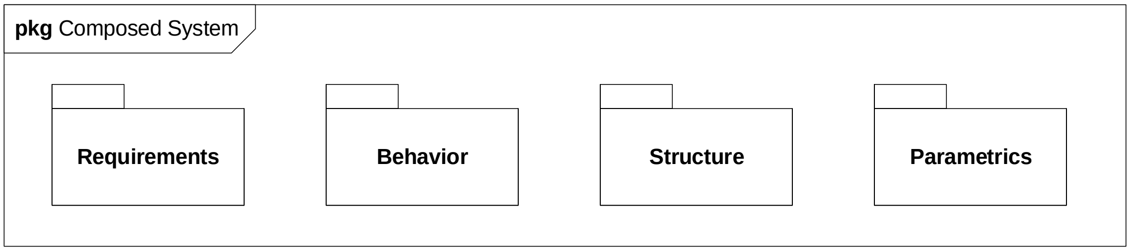

Figure 21: Package diagram showcasing the four elements, or "folders" of the composed system

Requirements Diagram

The first folder within the package diagram is the requirements folder. This folder contains the requirements diagram, which maps user requirements based on their hierarchal nature to each other. Each requirement box has a title, an optional id, and can optionally include the original requirement text that that this requirement derives from. A further step not shown here is to take these requirements diagrams and map them to the feature that explicitly meets that requirement. Figure 22 presents the requirements diagram for the composed system. As can be seen to meet the requirement that the system be able to compose seven or more processes (seven was arbitrarily chosen by the authors) requires meeting the child requirements. These sub requirements involve having a sustainable assessment feature, and ensuring that all processes are compatible. Both of these child requirements have child requirements of their own. For example, to be compatible a process must be meet the constraints of the linking process and be capable of accommodating the transiting workpiece based on material and geometry properties.

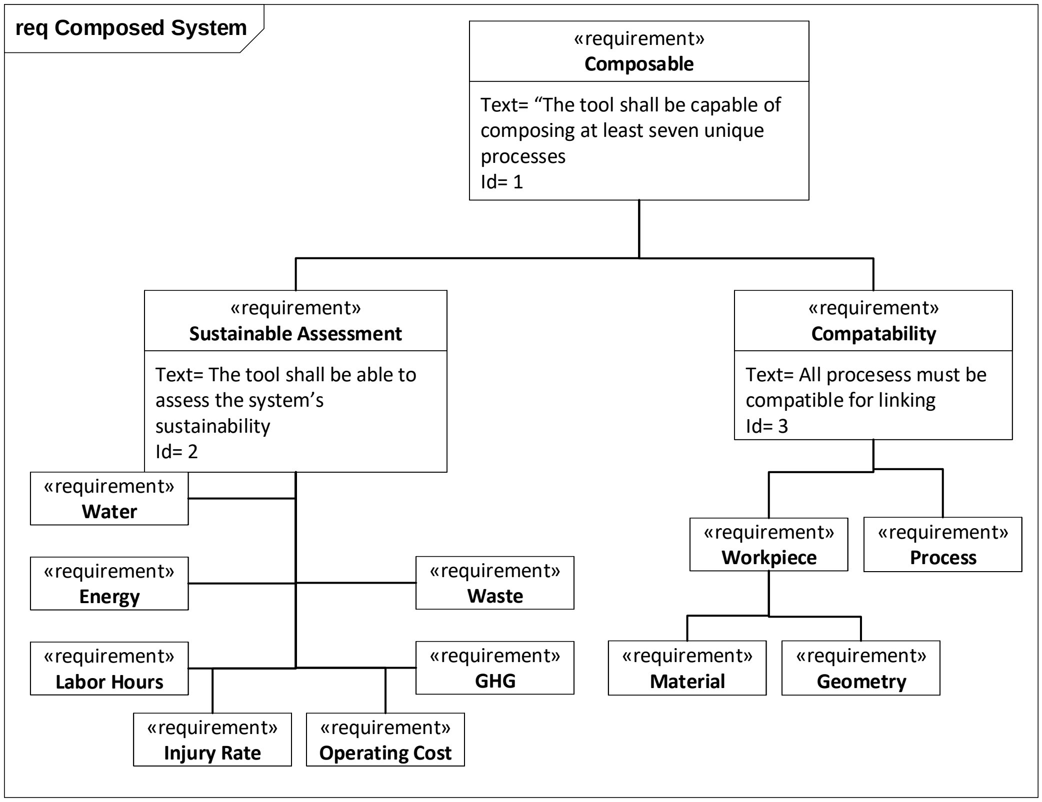

Figure 22: Requirements diagram for a composed system that is capable of correctly linking processes and performing sustainable assessments

Activity Diagram

Activity diagrams show a different angle of the system. Instead of visualizing the conceptual structure of the system, behavior diagrams such as activity diagrams visualize the physical interaction of a user with the realized system. Friendenthal et al. described activity diagrams as traditional flow diagrams but with added capabilities [208]. The building blocks represent actions. Each of their pins accepts inputs and outputs. Actions are atomic and should represent basic functions as recommended by Pahl et al. The activity diagram tracks the sequence of events in which a user composes a system (figure 23). In this sequence a user, represented by the black dot, starts the activity by selecting a workpiece to be inputted into a process. This process is also selected by the user. Once both workpiece and process are selected, then the process operation is performed. Upon which, the workpiece exits the now expended process and is ready to move on to the next process or the end customer. The user links the past process to a new one selected from a list of all compatible following processes. At this stage, the user faces a choice. If the system is fully composed, then the user moves on to performing the sustainable assessment. Otherwise, the activity repeats and the user selects the next process and performs the process.

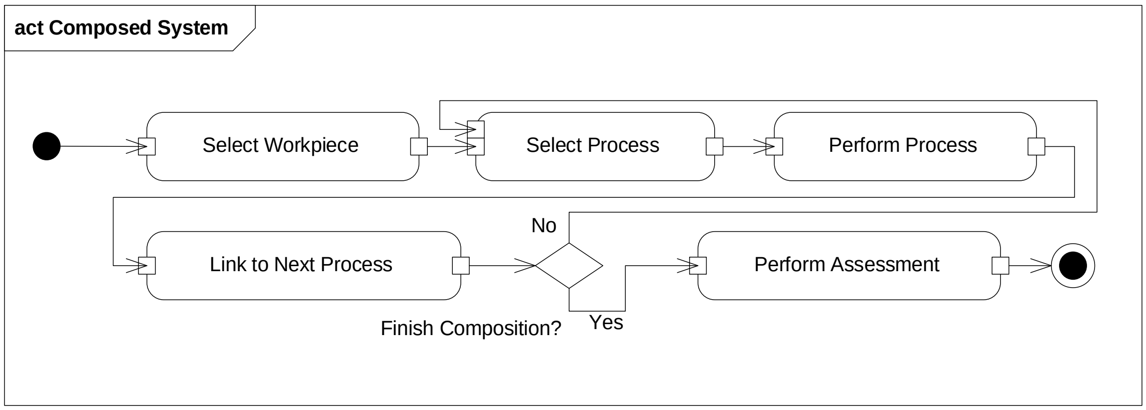

Figure 23: Activity diagrams of the composed system shows the actions taken by the user from start to finish

Block Diagram

The block diagram defines blocks, their features, and the structural relationship with other blocks. Figure 24 visualizes the hierarchical structure of a composed system. In this case, blocks represent both physical and software elements. Blocks are like classes in object oriented (OO) programming. This means that each block is template from which child elements are instantiated. Five blocks represent the composed system. For each block values and their units are specified in a manner very similar to how classes are developed in OO programming. In this example, the process being considered is tempering, which has a value representing the oven temperature measured in kelvins. The workpiece is a piece of 7040 steel with final yield strength measured of 300 MPa after tempering – note that the actual MPa value is omitted in the diagram. The sustainability block represents the specifications used to measure performance of the system. For example, GHG emissions of the composed system can be assessed in units of CO2 equivalent. Finally, the linking block constitutes the requirements to connect one process to another. This requires that the processes be compatible, as noted in the requirements diagram. Mathematically, compatibility can be represented using Boolean logic, where a true value indicates all requirements are met, and a false value indicates incompatible. Taken together the blocks represent the entire system, and on account of their intended similarity to classes, this block can be quickly implemented and utilized in software form. However, there are still specifications that must be clarified in order to implement a robust software tool. In particular, while it is now understood how abstractly the five blocks constitute the system, there is still questions as to the internal dynamics of the blocks, and the interactions between.

Internal Block Diagram

The internal block diagram (IDP) identified the relations between blocks structured earlier in the block diagram. IDPs evaluate how working principles (blocks) interconnect to create working structures (systems) [207]. The same figure 24 that visualize the blocks can also be used as an IBD, by virtue of the small system being modeling. The IBD takes the blocks discussed earlier and connects them based on their information or material flows. There is no starting point within an IBD, the intent is simply to show the interconnectedness of the system. What figure 18 does show is that each block answers to one or more sibling blocks, a reflection that must be implemented in software form. It should be noted that there are many solutions to every function structure. The solution represented in figure 24 is one of many different conceptual and paper approaches to modeling a system.

With the flows between clarified and represented, the final step in systems modeling is to model the flows of information as parametric equations linking one block to another.

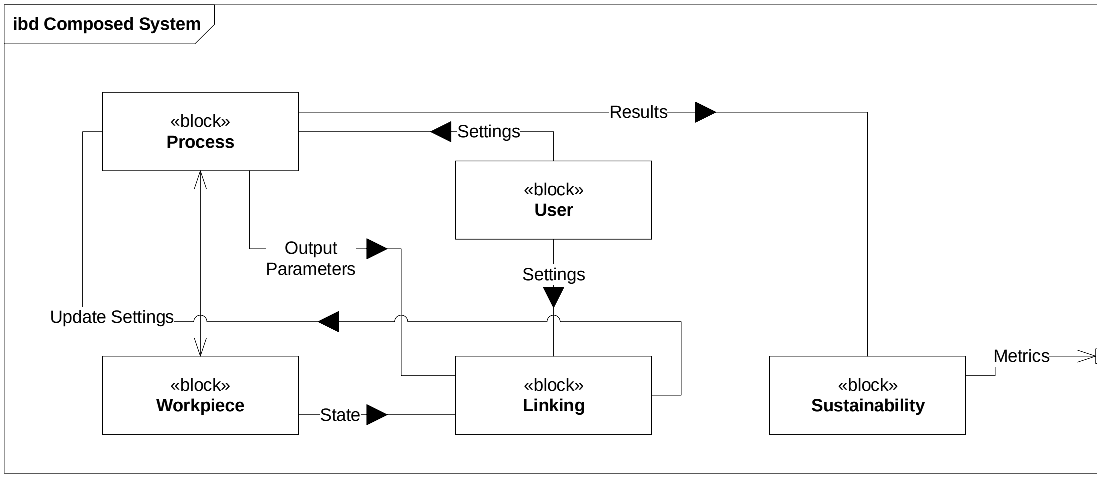

Figure 24: Internal block diagram of composed system showcasing relations and flow between of system blocks

Parametrics Diagram

Parametrics diagrams capture the constraints of a system. These constraints can then be evaluated by an analysis tool. Constraints are expressed as equations where the parameters are bound by the system. Each parametric model can capture a particular analysis section. This means that more than one parametric diagram can exist for a system. Only one is presented here (figure 25). To enable parametrics diagrams SysML introduces the constraint block. A constraint block is similar to the standard block used earlier, but is intended for use with equations that can be reused. Constraint blocks define parameters and the expressions in which the parameters live. Figure 25 demonstrates that in order to compose tempering with shot peening, several constraints must be met. Using the constraint blocks, parametric diagrams visualize the system of equations needed to meet the constraints. For example, the constraint block *coverage calculation* involves three equations required to solve parameters. These equations are: *m* the mass flow rate, *roe*, the shot density, and *d* the shot radius. With the coverage calculation equation now ready, a system of equations as presented in figure 25 can be seen as taking inputs from the other blocks identified in the IBD (figure 24) transforming them through a system of equations, and outputting the results. These results could then constitute the inputs to another parametric diagram, e.g., sustainability, to calculate the injury rate or labor costs, among other options.

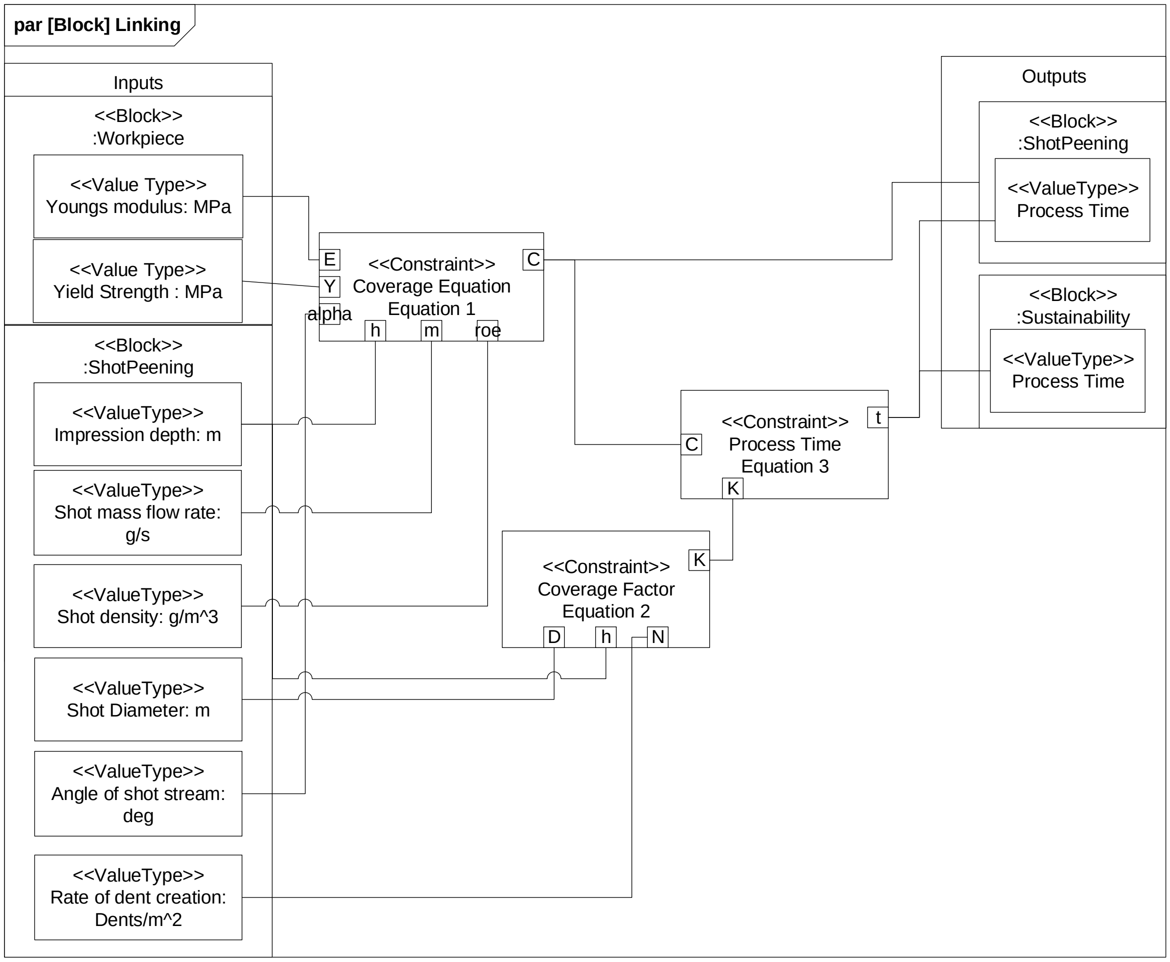

Figure 25: Parametric diagram of the linking block. Inputs from the processes and the workpieces are modeled using unique to the instance constraint equations to produce outputs that can be used to perform systems assessment or inputted into the composed process

Information Architecture

The fifth row of the Zachman framework contains the detailed models required for implementation. Techniques and modeling languages capable of satisfying the requirements of row five are very specific to the task at hand, as they enable realizing the information model. To this end, this paper proposes an actionable XML Schema that can structure process and composable data to standardize information analysis in software format. XML is a markup language that formalizes a set of rules to govern encoding documents. XML documents are both human and machine readable. The design goals of

XML are simplicity, legibility, generality, and usability across platforms and the web [53]. XML has become widely adopted as a common data format platform.

In this research, an XML schema was developed capable of covering all composed UMP models. An XML Schema describes the structure of an XML document. It defines the building blocks of an XML document including: the elements and attributes that can appear, the number and type of child elements, data types, and default and fixed values [189]. With this in mind, the proposed XML Schema covers the building blocks of UMP models, and further specifies the requirements for composing UMP models. Manufacturing processes are diverse, and attempting to shoehorn them all into the same schema runs the risk of reducing the accuracy and value to any one xml process model. Linke et al [74] noted this to be true with grinding processes. Material removal rate (MRR) is a common performance metric for processes such as milling, however, it is less useful for measuring the performance of a grinding operation, where the intent is not to remove material, but to improve surface finish. Thus, an XML schema must allow for variations in XML documents to better reflect the makeup of its modeled processes.

Schemas, by design, allow for variation in referenced XML documents so long as the schema writer is cognizant of the variation and structures the schema appropriately. For example, a schema controlling the composability of manufacturing processes must be capable of handling a diverse set of potential process imparted transformations (figure 26) for different process categories. These transformations are important, as they enable composing UMPs by virtue of the workpiece carrying the information of that transformation through a common variable. If a common variable is unavailable, then the transformation must convert one variable to another for use by the following UMP. For instance, tempering is a structural modification process that changed the mechanical features of the workpiece; it increased yield strength. The workpiece then carried this yield strength information to shot peening where it influenced the duration of the shot peening operation. The sequence repeats and the workpiece moves down the line.

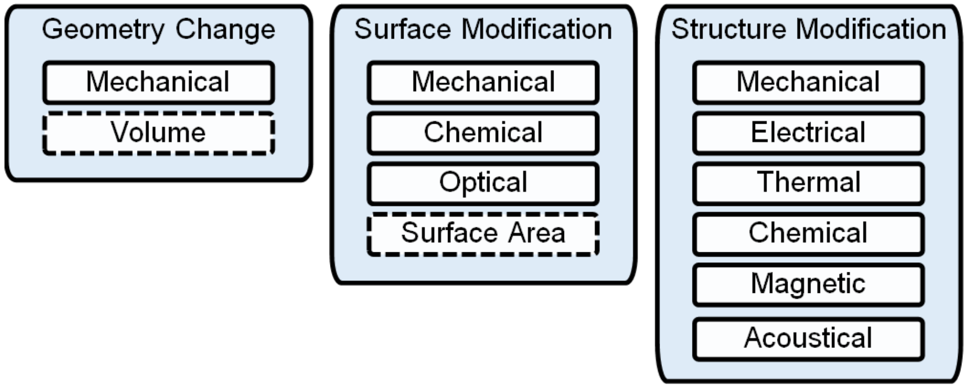

Figure 26: UMP categories and relevant modification areas that can be modeled using the proposed XML schema

The Schema developed herein is structured following the structure diagram in Figure 27 to specifically allow any composed system to be modeled. Process diversity is accommodated by using generic child elements of the parent *UMPs*. Furthermore, more than one *UMP* can exist within one *ComposedSystem*. Each *UMP* has child elements: *Inputs, Outputs, Transformations, and ProcessAttributes*. Each child element then has its own attributes to categorize different inputs. For example, a grinding process belongs within the surface finish category. Grinding could be documented using the element *UMP* but with different *Transformations*, and *ProcessAttributes*. Within the *Transformation* element, instead of material removal being mathematically modeled, a series of equations to assess surface quality could instead by labeled by the Schema. This approach of using descriptor elements generalizable to all processes maximizes code reusability and minimizes Schema size. The alternative, which was investigated, is to develop separate slave schemas under the control of a master schema, where each slave schema controls one process category. This approach inherently involves duplicating many lines of code, and for very little gain, since the generalizable Schema proposed herein allows for uniqueness.

The second portion of composability is the act of linking processes together. As can be seen in figure 27 this action deserves its own child element that is a sibling to the UMPs element. The element Linking describes the actions required to link two or more processes together. To do this, the Schema dictates that a user must specify a target and source UMP, the input and output variable, and the unique transforming equation(s) between the variables should the user want to compose two or more processes. Equations belong within the *Transformations* element. This element is identical in description to the Transformation element within the UMP element. Furthermore, the Linking element of this Schema establishes a specific compatibility element to allow for users to enter any and all processes that are either forwards or backwards incompatible with this process, i.e., surface finishing operations should not be followed by a material removal process. Note that in the case where a common variable exists, then the input and output variable are the same. Furthermore, there can be more than one *LinkingAction* with a composed system. For example, Figure 28 presents a potential case where one *LinkingAction* includes a *transformation* using one common variable. In this case no equations exist. Another possibility is to equate an output variable from the first UMP to an input variable of the following UMP. This would give a designer the option to develop and use the transformation that is more accurate at transferring information without accuracy loss from downstream to upstream processes.

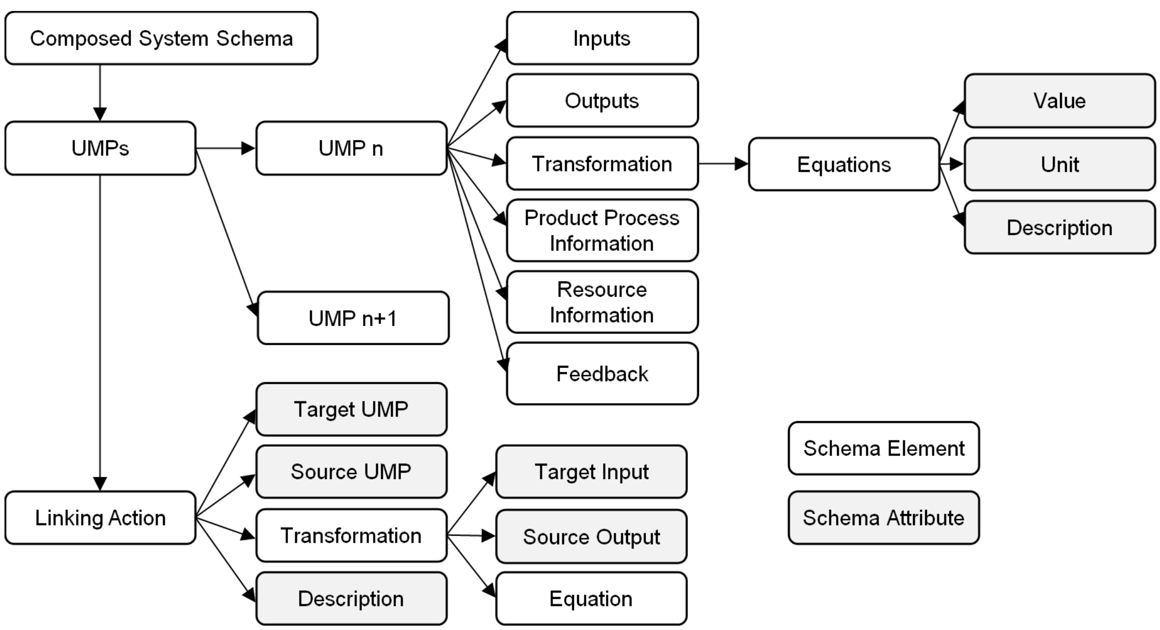

Figure 27: XML parent-child diagram showing elements and attributes

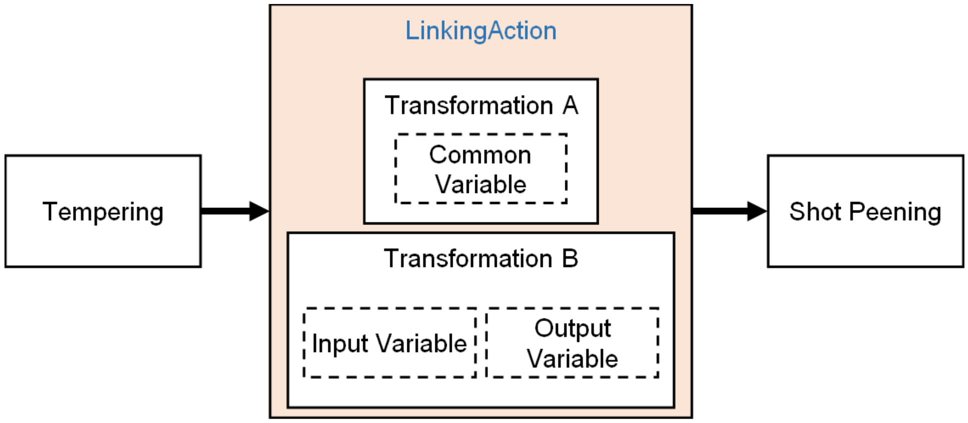

Figure 28: Conceptual look at LinkingAction where one or more transformations may occur but with differing variable scenarios

Discussion

The XML Schema code is presented in Appendix B. For each XML document, the *inputs*, *outputs*, *transformations*, *feedback*, *processproductattributes*, and *resourceinformation* contain information unique to the process. The user is allowed strong leeway in determining which element best fits known information, however, the two XML formatted models herein were categorized with guidance from current ASTM standards [18], [198], and it is advised that all users utilize the standards for aid in populating an XML document. The XML code for the composing of Tempering to Shot Peening requires less information, and is more specific (Appendix D). The mathematical composability model presented earlier (Eq'ns 1,2, and 3) can be seen in Appendix E as being fully captured within the XML *Linking* element. The child *LinkingAction* element extends the parent *Linking* element to include the source UMP and source output, as well as the target UMP and target input. The transformation that occurs as evidenced in equations 1, 2, and 3, are captured using the *Transformation* element. The variables present in the *Transformation* element are captured using another child element title *EquationVariables* to capture the variables that are present in the transformation of *SourceOutput* to *TargetInput* Moreover, these models were illustrated graphically using the SysML diagrams. The benefit of graphically representing the equations was to illustrate the elements within a manufacturing system that rely on the equations to convert output into usable input information. In the XML Schema room is given for a user to enter further metadata on any element if the user deems it necessary or valuable, thus for each UMP *type* is specified following the taxonomy of Todd et al. [20]. In this taxonomy, UMPs belong to one of two primary fields based on whether the process removes material. From there the two primary classifications are subdivided into smaller groups.

In summary, the objective of the work conducted herein was to develop a layered information modeling framework. Each layer covers a different aspect of the information flows within a manufacturing system. The objective of the first layer was to elucidate the relation between sustainability performance indicators and the UMPs within the manufacturing system. IDEF0 was used to functionally represent the flows of information between UMPs and sustainability indicators. However, alternative techniques could be used in place of IDEF0. IDEF0 can become illegible and cumbersome when the number of indicators grows larger than six, as it did in the representative manufacturing system presented earlier in this research. The objective of the second layer was to understand the information flows between UMPs to aid composing. This was achieved in this work through the application of SysML diagrams to graphically represent the key elements within the system, their definitions and relationships, and the specific requirements needed to enable composing. While SysML worked well for this application, it required extensive knowledge of computer science domain ontology. Thus, this technique may struggle to find acceptance with industry practitioners unfamiliar with computer science knowledge. Finally, the objective third layer was to develop an architecture to structure and label the information within a manufacturing system. placing information into schema controlled XML documents allows for reuse and sharing. The widespread use of the presented Schema would greatly reduce the current ad-hoc nature of UMP modeling. Furthermore, the common Schema reduces the amount of irrelevant or duplicate information stored within the XML documents. This reduces the time required to populate the XML documents, and further reduces the computational burden on readers to understand the captured information. In addition, because XML is machine readable, the reduction of duplicate information and standard method of entry also opens the possibility for efficient software implementation. However, there are limitations to the use of XML. Firstly, it is verbose and this translates into reduced ease of human legibility and larger overhead processing. While in a small example the larger overhead is negligible, if a repository of XML formatted UMP models is to exist, then overhead must be minimized to facilitate data transfer and data query.

Conclusion

UMPs hold a wealth of information that remains underutilized. This information holds the promise of improving UMP models and composing UMP models to produce interlinked manufacturing system models. However, to properly utilize this information, a framework must be developed from which standards can arise for use by industry in the design for manufacturing domain. Otherwise, information risks becoming utilized in an ad-hoc manner, with little thought for compatibility between user models. Previous information models have focused on product and process level understanding, while sustainable manufacturing has focused on modeling UMP and manufacturing systems as distinct entities. Only recently have efforts been invested to integrate the process and system levels, while this work is the first to present an information model and framework to compose UMPs and produce holistic manufacturing systems capable of being assessed on their sustainability.

This research proposed a framework to proactively mitigate the risk of ad hoc composability methods developing by suggesting methods to visualize and utilize process information for the purpose of improving process model accuracy and enabling model composability. Additionally, the proposed schema holds the potential for actively reducing the current ad-hoc nature of UMP modeling, by strictly specifying what information a user must enter to fully characterize a UMP. With UMP models characterized in the same manner, they could be shared among researchers and industry participants and reused in multiple analyses. Furthermore, by providing Schema elements for composing two or more UMPs, the Schema can extend to cover the modeling of manufacturing systems containing more than one UMP. Thus, not only could UMP models be shared among researchers and industry participants, but so could fully modeled manufacturing systems.

However, this work was limited in scope to only consider a composed manufacturing system consisting of tempering to shot peening. In this work only two UMPs and one linking action were characterized. Characterizing more UMPs using the XML schema would increase the corpus of available case studies while also acting as a quality checking tool for the Schema. It is entirely possible that different UMP types may require the addition of new descriptor elements or attributes. Furthermore, as prior research and this research have attested, there can be more than one linking action between neighboring UMPs within a manufacturing system. Future work should investigate other alternative linking actions to the one presented in prior sections. Having more than one linking action would allow a designer to select the most appropriate connection between UMPs that best preserves parameter decisions. Finally, the framework facilitates the development of software by identifying the information required and its flow between physical and non-physical objects. This flow of information could be coded using object oriented programming to produce an application expediting composing and assessing manufacturing systems. Future work will focus on developing such an application.

Acknowledgements

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CHAPTER FIVE: A DESKTOP APPLICATION FOR SUSTAINABLE ASSESSMENTS OF COMPOSED UNIT-BASED MANUFACTURING SYSTEMS

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CHAPTER 5: A DESKTOP APPLICATION FOR SUSTAINABLE ASSESSMENT OF COMPOSED UNIT-BASED MANUFACTURING SYSTEMS

Abstract

Life cycle assessment software packages such as SimaPro, GaBi, and Umberto have in past years become well established tools for conducting environmental impact analysis. However, applications for broader sustainability assessment are limited. Recent research has developed an information modeling framework to compose unit manufacturing models for sustainable assessment and has led to the definition of unit manufacturing process information modeling concepts. An engineer can use the framework to generate a manufacturing system sustainability assessment by composing unit manufacturing process models. The results can aid engineers in selecting the superior manufacturing system for a given product. To demonstrate usefulness of the information framework, a prototype desktop application was developed. The application was implemented in Windows Project Foundation (WPF) using C# as the coding language to create a graphical user interface. Mathworks MATLAB serves as the calculation engine. Unit manufacturing process models are written following the framework and then read by the application, which then produces a sustainability assessment for the manufacturing system. An automobile-like metal product manufacturing system acts as the case study demonstrating the use of the application.

Introduction

Companies, individuals, and governmental organizations continue to strive for superior sustainable manufacturing systems. Corporate responsibility programs have been implemented in response to the growing energy demands and higher energy and material costs [209]. This external pressure has begun to mold company and individual cultures and attitudes towards consideration of sustainability (economic, social, and environmental) performance a central tenet of operations.

Despite this strong belief by consumers and companies, energy use is expected to continue to rise as affluence increases [210] and manufacturing moves towards high energy processes [116], though it has negative sustainability implications. This energy use is due to activities across the residential, agricultural, commercial, transportation, and industrial sectors, with the industrial sector accounting for 31% of total energy use in the U.S. [211] and one third of all global energy use [163]. As demand for commodities grows, companies are responsible for large impacts on society and the environment [212].

Since the Brundtland Commission report in the late 1980s, many assessment methods and tools encapsulating those methods have been developed for analyzing industrial sustainability performance. As companies search for opportunities to improve sustainability performance, they require new tools to uncover opportunities that older tools cannot provide. Many existing tools are meant for evaluating impacts at a national or regional level, and provide few meaningful results for product and process designers [213]. Thus, the development of new tools is required that encompass the three aspects of sustainability and are intended for use by engineers early in product design and manufacturing [214]. For example, the suite of tools currently available for conducting life cycle assessment (LCA) does not facilitate process-level analysis, leaving this area of focus in need of new tools.

The goal of the research presented herein is to realize a theoretical information modeling framework within a desktop application to assess the sustainability performance of metal component manufacturing *a priori*. The information modeling framework adopted for labeling and composing unit manufacturing process (UMP) information flows has been reported in prior research [159], [215]. The next sections present further motivation and background on the research topic, the assessment methodology and information framework, the application architecture, an application demonstration, demonstration results, and next steps to be undertaken.

<u>Background</u>

The most well-known applications for sustainability assessment (e.g., SimaPro and GaBi) share LCA as their common assessment methodology. These applications give engineers a start in making informed environmentally-related decisions in their design space, however they suffer from a critical limitation. LCA applications cannot support system, process, or machine level sustainable manufacturing decision making [11]. LCA is most appropriate for performing environmental assessments of each stage of a product's life, from extraction to disposal, but does not allow for in-depth manufacturing process assessment. LCA struggles to account for broad social impacts, focusing on more direct health effects.

Furthermore, of the LCA applications available, researchers have noted several deficiencies. For example, LCA-based applications are not design-oriented, checklist applications provide guidelines rather than solutions, and quality function deployment (QFD) based applications rely strongly on the knowledge of the designer [84]. Moreover, LCA is marred by a number of operational deficiencies, such as cost, complexity, and large time investments, multiple competing standards, and the reliance on subjective value judgements [12], [13], [15]. Despite these deficiencies, many LCA applications (e.g., GaBi, SimaPro, Quantis, Earth Smart, and Umberto) have been developed to assist designers in making informed decisions.

Methods proposed for assessing social impacts have led to development and implementation of alternatives and applications complementary to LCA. One example, from the human factors domain, considers the NIOSH (National Institute of Occupational Safety and Health) lifting equations [216], which were implemented into an MS Excel-based tool [217]. Another example intended to integrate with LCA using new metrics such as Days Away from Work (DAW) with data sourced from the Bureau of Labor Statistics [218]. Other methods have been incorporated into LCA software, such as the ReCiPe method for calculating mid-point impacts on human health (e.g., carcinogenicity). However, these calculations are tied to material and energy inputs and outputs of the system under study, and are not necessarily scalable to individual manufacturing processes or manufacturing locations.

This inability of LCA applications to account for manufacturing process level sustainability performance has been recognized as a need within the manufacturing research community [13]. In response, new methodologies such as unit manufacturing process (UMP) characterization for sustainable assessment [6], [18], [22], and unit process life cycle inventory (UPLCI) [102] have been proposed. The relative youth of this research field has meant only a few prototype applications utilizing sustainability assessment methods have been reported. Garretson et al. [99] developed a Visual Basic application with the capability to assess and compare the sustainability impacts of alternative manufacturing process flows. The application was built upon the UMP characterization method presented in [22]. The application provided solutions without requiring sustainability information from the user, a design element previously identified as necessary for widespread use of such tools by Chiu and Kremer [219].

While more recent applications [99] give developers greater ability to make informed decisions. Smullin etl al. [14] recently noted that industry is reticent to adopt new applications without substantial improvements in the accuracy of the underlying UMP models and manufacturing system models. One method to improve the accuracy of manufacturing system models (also known as manufacturing process flow models [9]) is to compose, or link, UMPs. Thus, composability refers to the ability to link UMP models together such that information flow between UMP models is preserved in a meaningful way [9], [25], [160]. In this manner, upstream process models can automatically be updated based on downstream process parameter changes and decisions (e.g., replacement of a manufacturing process). This flexibility can lead to more accurate process modeling and system assessment [197].

To improve UMP model accuracy and composability requires new research into information frameworks controlling how an engineer captures and classifies UMP data. Information models have been developed to control product information [181], [182]. No work has been reported, however, save for the recent work by Zhang et al. [137], that has attempted to integrate sustainability assessment with UMP information and process modeling. In response to this research gap, Chapter 4 proposed an information modeling framework to assist the composing of UMP models for sustainable assessment. For the usability and usefulness of the framework to be demonstrated, an application was developed to assist in conducting manufacturing system sustainability assessments by semi-automating the composing of UMPs and the automation of the final assessment.

Before discussing the actual application, information on the underlying methodology is presented in the next section.

Sustainability Assessment Methodology

The sustainability assessment methodology underpinning the application borrows from several methods, each developed in response to deficits identified in the literature. The first step in developing a sustainable assessment application was to select appropriate metrics for each UMP model. In previous research, UMP models were aggregated for system level assessment of products during design for manufacturing. The crucial fault in this approach is the severance of the traceability of system level metrics to the constituent UMPs. This leaves designers with only a fuzzy understanding of how UMP process parameters influence system performance. Thus, calculations must be identified that relate and quantify the chosen metrics and values for each UMP.

The first step in developing such calculations was the identification of useable sustainability metrics. The metrics used herein were first proposed for use in a method by Eastlick et al. [164], expanded by Eastwood et al. [114], and implemented by Garretson et al. [99]. To assess the manufacturing system, the metric results for each constituent UMP in the system are aggregated. For comparison purposes, the results are then normalized following the method of Garretson et al. [22]. This method can be summarized by the following steps: 1) define the goal and scope of the study, 2) select and quantify the sustainability metrics to be evaluated, 3) define the key unit manufacturing processes involved in production, 4) construct mathematical models of the unit processes, 5) apply the models, and 6) analyze the assessment results.

To improve the accuracy of the system assessment, each UMP model in the manufacturing system is composed, which allows the transfer of product (workpiece) information from one process to the subsequent process. Composing of two or more UMPs requires identification of relationships between neighboring UMPs in the process flow. These relationships identify the variable(s) common to each UMP. In the absence of a common variable, a source variable from the downstream UMP is mathematically translated into a target variable readable by the upstream UMP. This method for composing UMPs was proposed by Garretson et al. [41] and later expanded in Chapter 4. The method borrows computer science techniques to standardize UMP composability and information capture and use.

In this work, the information framework of Chapter 4 and the accompanying application are demonstrated by comparing two design alternatives for an automobile-like component. Seven metrics were selected based on applicability to automobile design and manufacturing, and incorporate the environmental, economic, and social aspects of sustainability. The metrics chosen include operating cost, onsite energy consumption, water use, greenhouse gas (GHG) emissions, total waste, acute injuries, and chronic illnesses. Additional discussion of sustainability metrics has been provided by previous research [29], [46], [48], [78].

After the metrics were defined, manufacturing processes were then selected for modeling based on their use in the production of the automobile component under consideration. A number of the manufacturing processes identified, e.g., milling, are applicable to many products and, thus, the modeled component acts as a good demonstrator of the abilities of the application and the underlying framework. Thus, their applicability is not limited to automobile manufacturing.

UMP models were developed in earlier work [220], while the mathematical transformations underpinning the composed process models were developed in-house [197]. The UMP models quantify each metric selected above using part geometry, process specifications, and/or design engineering parameters as inputs. Because performance metrics are calculated based on these parameters, quantifiable process-based metrics are needed, rather than more typical qualitative sustainability metrics.

Thus, the UMP models developed could then be composed to generate a system-level assessment. Using a database of unit manufacturing processes and relationships for their composition, along with design specifications, design alternatives could then be assessed and compared to one another using a desktop application. The design and operation of the desktop application is described in the sections below.

Application Architecture

With the method and supporting models developed, the need emerged for a specialized application capable of tracking the variables of the different processing operations, literature data, and modeling assumptions, and that could efficiently perform numerous time-consuming calculations to support analysis. Further, the application had to define the manufacturing line to produce a part as unit processes and linking actions, calculate the metrics, and organize the results for analysis.

The architecture of the resulting application is comprised of a calculation engine, UMP warehouse, controller, and graphical user interface (GUI) (Figure 29). The general flow of information is represented by arrows in the figure, with data being pulled by the controller from the warehouse and sent to the GUI and calculation engine. The GUI controls the user's interaction with the application. The user selects the desirable UMPs and links to be included in the manufacturing system model, and inputs the new process parameter values for each UMP. The calculation engine receives process equations populated by the user's numeric input and solves the process equations. These results are then used by the calculation engine to calculate the performance metric values for each UMP and then aggregate the results. With the requirements understood, the next task was to peruse literature and consult experts to determine the programming languages and methods available to construct an application, and finally to settle upon a superior approach.

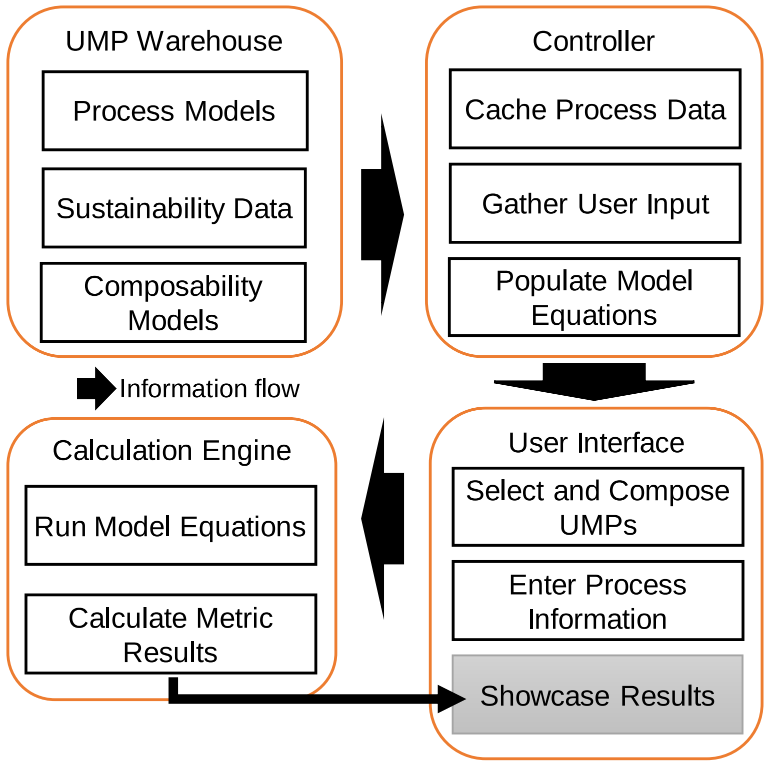

Figure 29: Structure of the software application

Application Design

In pursuit of developing an application design, there were decisions to be made in determining what programming languages would be selected, what platform was preferable for the intended use, and what integrated design environment (IDE) would be the most amenable for this task. The first decision was to select a programming language.

Programming languages belong to one of three domains according to Ousterhout [221]: assembly, system, and scripting. More recently, this understanding of language domains has shifted to define system languages and application languages. System languages are fundamental languages (e.g., C) that allow for elemental architectural decision making, including abilities such as memory allocation. System languages provide the largest scope of control at the expense of programming speed. For a proof-of-concept application for the task at hand, this domain of languages would be excessive. Application languages (e.g., C# or Java) provide the greatest balance between control and time efficiency; a line of code in an application language can represent 100 to 1000 lines of code in a systems language. A scripting language, such as Python, lacked the modularity desired. [221]

To develop the proposed desktop application herein, C# was chosen to be pursued. The balance of capabilities with efficiency was deemed sufficient for the task at hand. Moreover, C# is a Windows-centric language, which offers a good fit for previously developed MS Excel-based models by the research team. Subject matter experts within companies consulted regarding sustainable manufacturing assessment were quick to note that manufacturing companies are strong Windows users, and maintaining systems compatibility would be integral to improving new application adoption [14]. The most robust IDE for C# is MS Visual Studio, hence it was selected for developing the GUI and the C# code-behind that powers the application.

The next decision was to determine whether the application would be desktop or web-based, as each offered benefits to accessibility and use. A desktop application is simpler as a proof of concept, requiring no additional programming language or supportive architectures. Desktop applications also offer robustness and security, where the only constraint to performance is the capability of the desktop CPU and GPU, whereas the web is constrained by the bandwidth of the internet connection. Security is less of a concern by reducing interaction over the web. A web-based program, on the other hand, offers greater usability. A user could access the composability application from any internet connected location, without the need for downloading software. Upon consideration of these benefits and drawbacks, a desktop application was chosen for its simpler implementation, greater robustness, and stronger security. The boost to usability of a web-based program was not sufficient to overcome inherent disadvantages of the approach.

The last decision needed involved selecting a GUI design environment. The most recent generation design environment offered by Microsoft is Windows Project Foundation (WPF) in Visual Studio. WPF is a presentation system where the core is a resolution-independent, vector-based rendering engine for modern graphics hardware. WPF also comes packaged with application ready toolboxes and features built upon the .NET framework. WPF, furthermore, can incorporate other features from applications within this framework, such as the ability to localize to mobile, desktop, or cloud-based environments [222]. WPF makes use of a programming language known as Extensible Application Markup Language (XAML) and is based upon XML. XAML is used to implement the appearance of the GUI, while another managing language (C#) controls the behavior within the controller module.

Application Structure and Operation

The application is comprised of multiple packages, classes, and folders. First, raw data is stored in user-made XML documents that conform to the XML Schema presented in Chapter 4. A user prepares an XML document by entering the UMPs for the manufacturing system along with the relevant information and the mathematical transformations of inputs to outputs required to model and compose the UMPs. With information inputted, the XML document is ready for pull into the application. The application reads each XML document with the assistance of an XML reader library and class and stores the XML data locally as strings. Upon reading and storing locally, the same XMLReader class parses each document by element and attribute to create a series of lists for all parsed data strings.

Figure 30 illustrates the operation of this class in the form of a UML class diagram. For brevity, only this class is presented here in UML format to serve as an example. The XMLReader class first sets a folderpath to the XML file folder, then it reads the composed systems within the XML documents and determines which equation variables directly relate to the chosen sustainability metrics. This class also delegates responsibility to two aggregated classes, called UMP and Link, which are responsible for reading and understanding the UMP and Linking portions of XML documents.

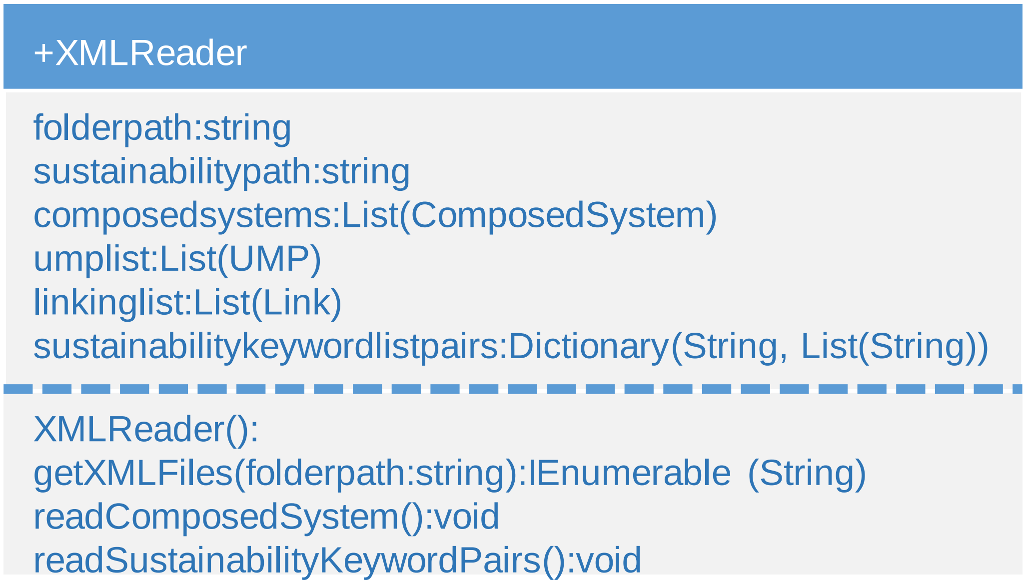

Figure 30: Example UML diagram of application XMLreader class

The same method is applied to each UMP's constituent mathematical relationships. Using different classes, each comprising equation within the UMP and LinkingAction sections of the XML documents is parsed and cached as a string. Each equation variable is later parsed from the equation string, and presented to the user through the GUI for value entry. Once the user enters a value and instructs the program to proceed, the XAML code-behind classes swap each equation variable string with its matching value. Once the application completes replacing each variable string with a value, the application passes the equation to MATLAB to calculate the system of equations solving in each case for the left-hand-side unknown (e.g. Y=ax+b, solve for Y) and receives the return value and caches it for later use in composing UMPs and performing system-level assessments.

The method in which the application composes more than one process can be visualized using Appendix C and figure 31. Appendix C presents a UML activity diagram for the composing core of the application. In the first swimlane (column), the user selects a source UMP "A" and target UMP "B" on the Compose page of the XAML GUI. The application then checks to ensure there is a linking action available for composing "A" to "B," and, if available, presents the linking actions. There could be multiple possible linking actions. The user selects the desired linking action, enters the parameter values for each UMP and the linking action, and then clicks *Link* to iterate and move to compose the next UMP in the manufacturing process flow. The application runs the models for “A” and “B” and stores the results for later use.

At this stage, the application no longer considers the process “A” model, individually. Instead, the linked UMPs are considered as one and “A_B” is loaded and primed for use by the application (figure 31). The user next selects this as their Source UMP, which is assigned the default name of “A_B.” Once the Target UMP is selected and the linking action also selected, the user clicks *Finish* to inform the application that the composed system is now complete and that the selected sustainability metrics can be quantified and evaluated. The application navigates to the Results page, and presents the sustainability metric results for this composed system by following the logic described by figure 32. The final results are the summation of each UMP’s sustainability metrics.

Should the user wish to compare alternative manufacturing systems on the basis of their sustainability performance, this is possible by navigating to the Comparison page and selecting up to three saved systems for comparison. Finally, the Warehouse page lists all the UMPs read and available for use. Figure 33 presents a compilation of screenshots of the application, with each of the aforementioned pages visible.

Since the application is built upon C#, and C# is an object oriented language, the code is comprised as a number of classes. Figure 34 is a code map generated by Visual Studio of the classes and interfaces (boxes) within the application and the associated connections (arrows). The width and number of arrows visualizes the strength of the connection. The core elements of reading the XML documents, extracting the UMP models, composing UMP models, calling MATLAB, and generating results all belong to their own classes. Other classes serve as helpers or fill niche roles. As with other programs, the judgement to what deserves being a class is subjective to the developer, though heuristics exist and were followed within development of the application [223].

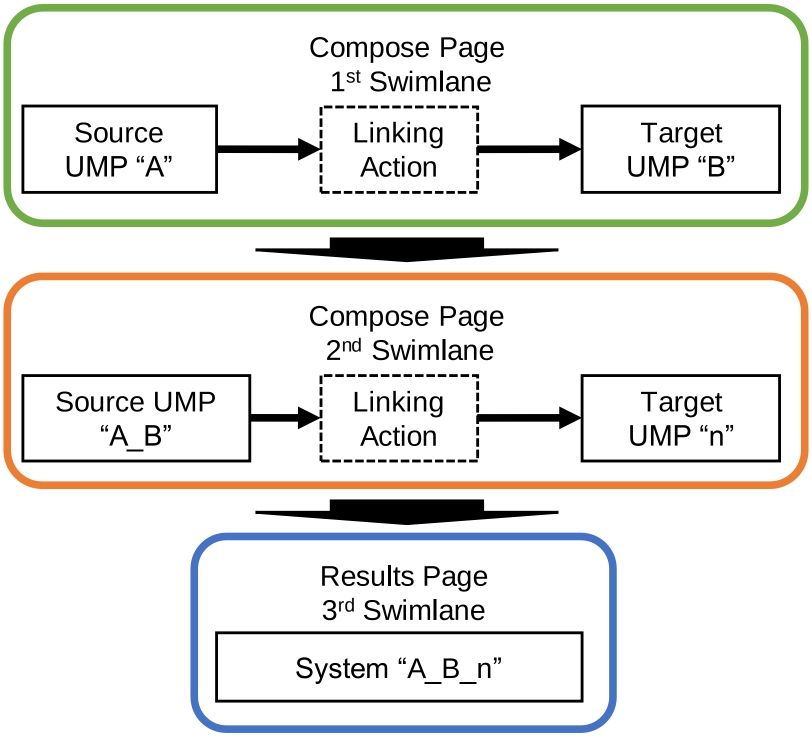

Figure 31: Implementation of composability through an iterative, linear process of system build up

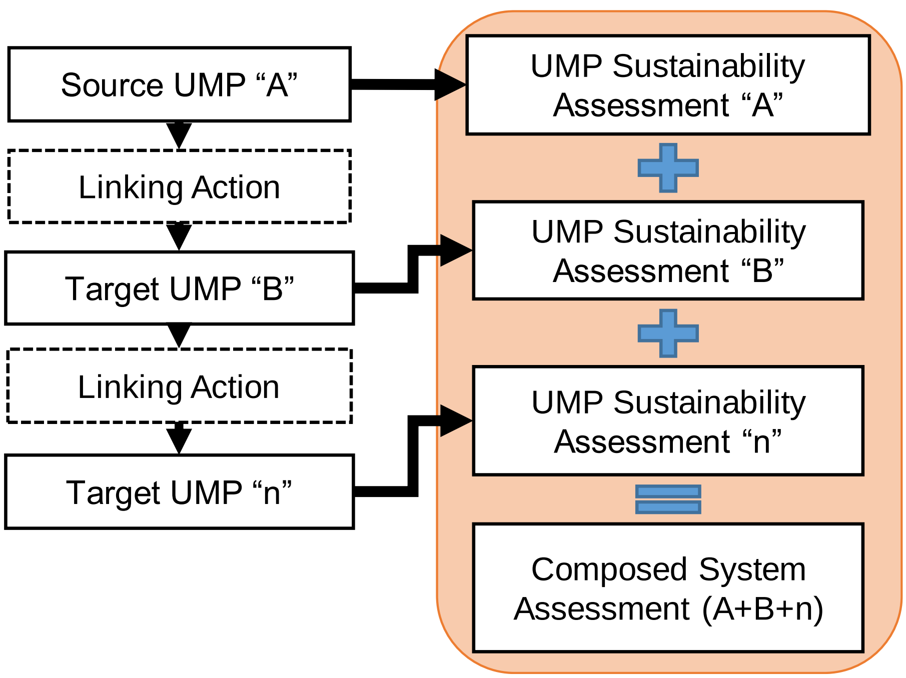

Figure 32: Final system assessment as the summation of each composed UMP's sustainability metrics

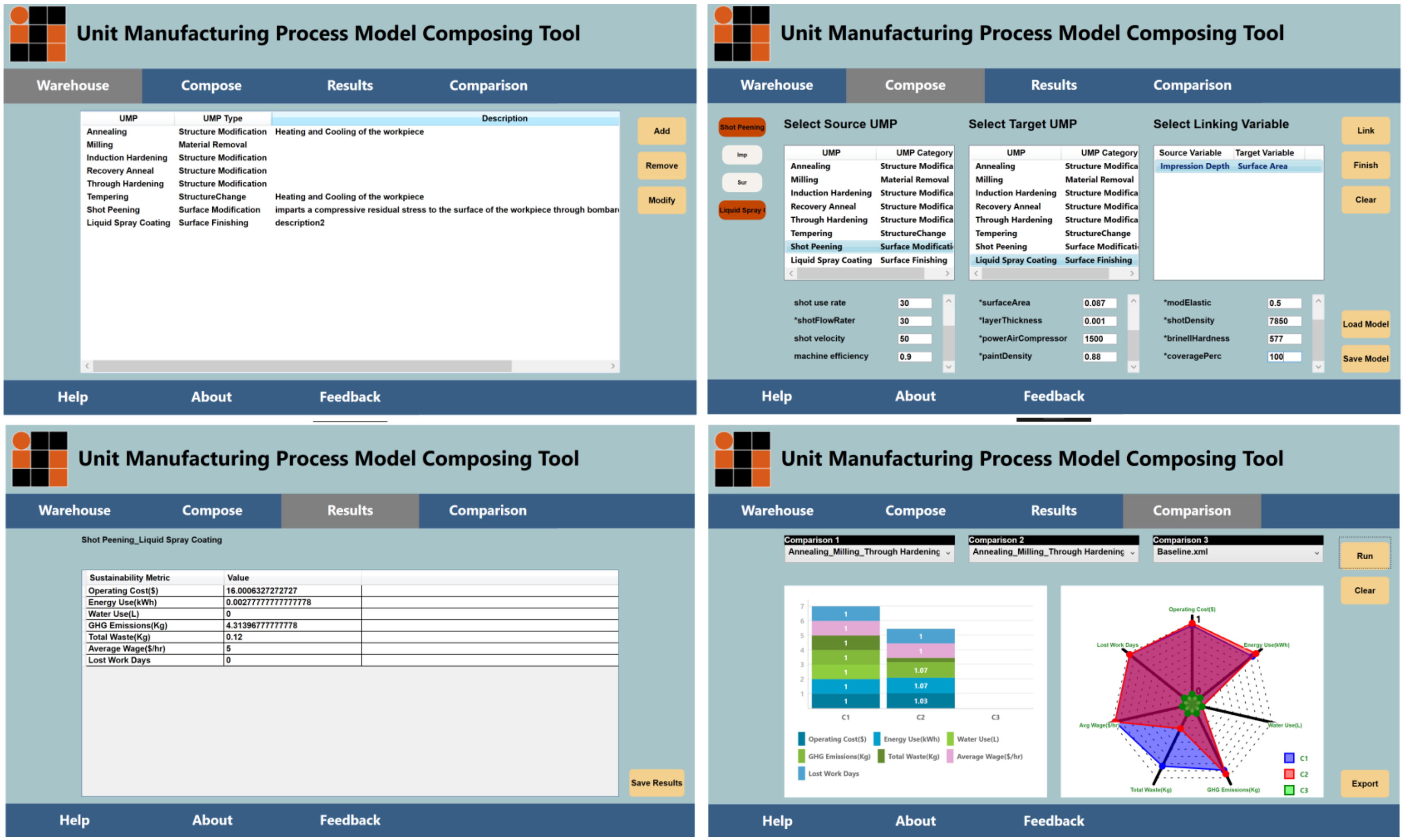

Figure 33: Application screenshots clockwise from top left: warehouse, compose, results, and comparison

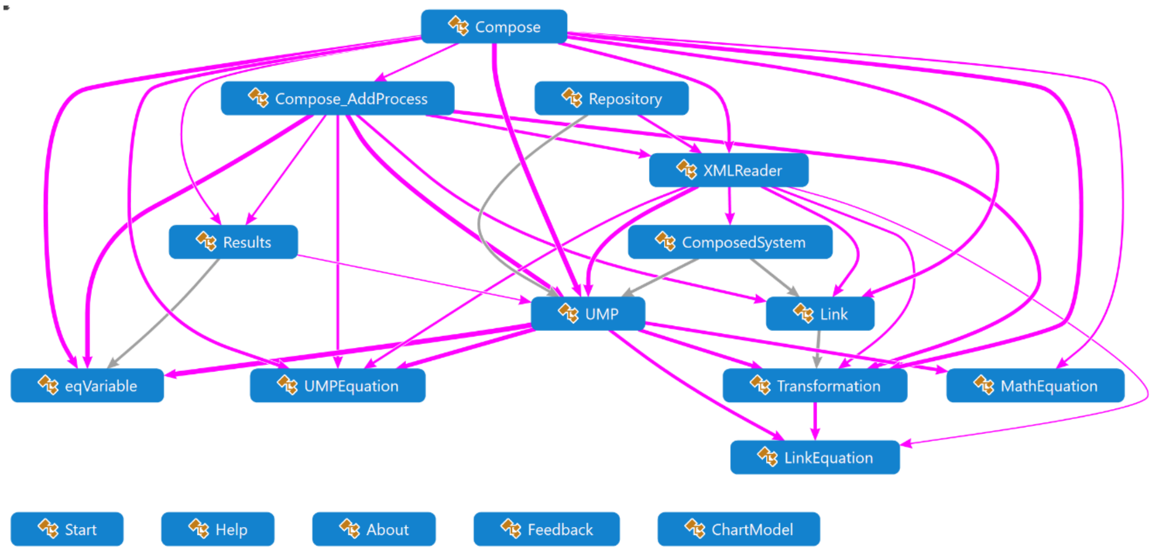

Figure 34: Code map of composability application with boxes representing classes and interfaces and arrows the connections between

<u>Demonstration of the Application</u>

The method and desktop application described above is used to evaluate and compare two alternative manufacturing systems for a single automobile-like part. The two system designs are assumed to be functionally equivalent. Methods for identifying functionally equivalent components are outside the scope of this work. The purpose of this demonstration is to illustrate the capabilities of the application to aid in design for manufacturing and assembly (DFMA) by bringing to light the differences in the respective sustainability performances of the two options.

The DFMA decision to be evaluated is the method for milling, surface hardening, and coating an automobile component for use (figure 35). Option 1 is to shot peen the part prior to spray coating (figure 36), while Option 2 is to induction harden the component prior to spray coating (figure 37). The shot peening process involves accelerating pellets to a predetermined velocity for impact into the component surface [167]. The impacts dent the surface, creating compressive residual stresses and improving the fatigue life of the component. Induction hardening involves passing a strong alternating magnetic field through the surface of the component to produce heat [224]. After reaching an optimal temperature and then quenching, the work surface hardness increases, while leaving the interior ductile.

The two manufacturing process flows represent the options for a decision an engineer might consider when choosing between two product design alternatives. With the desktop application, the designer could quickly evaluate the sustainability performance of each option and select the superior option as demonstrated below.

Figure 35: Automobile strut mounting bracket

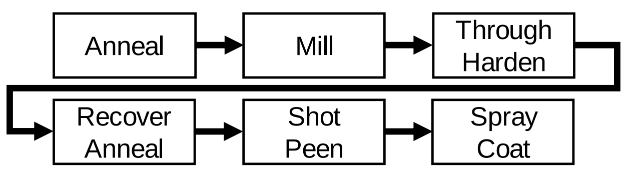

Figure 36: Manufacturing process flow option 1

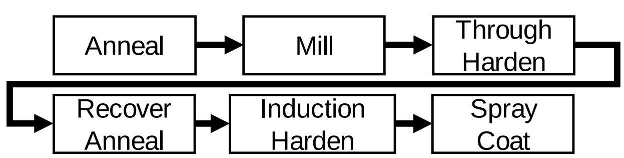

Figure 37: Manufacturing process flow option 2

<u>Results</u>

The manufacturing process flow for Option 1 and Option 2 were modeled in XML (Appendix C and D) and submitted to the application. Then, with the application presenting each parameter needed to the user, values were entered based on literature review. Results were next calculated and stored for each process flow. Table 10 presents the summary of results broken down by metric and process. Figure 38 presents a stacked column chart generated by the application. In this analysis, the resulting values for Option 1 are set equal to one. Metric values for Option 2 are then the ratio of Option 2 to Option 1 metric values.

The table and figure demonstrate that Option 2 is the superior manufacturing system. It should be noted, however, that the comparison approach applied here does not impart weighting values to differentiate the importance of different metrics (impact types). Looking at the individual metric scores, it is possible to reason that substituting shot peening for induction hardening results in lower impact due to lower material consumption at the expense of increased energy consumption. Since energy costs are much cheaper, the end result is to favor Option 2.

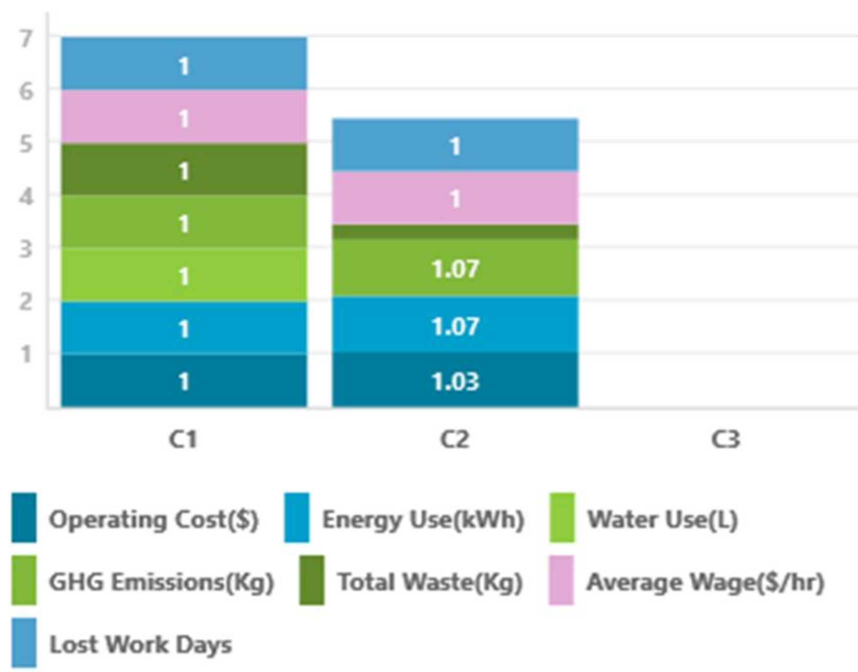

Figure 38: Normalized comparison of options 1 and 2

Table 10: Summary of sustainability assessment results

OPTION 1	Anneal	Mill	Harden	Recover	Peen	Coat	Total
Energy (kWh)	24.94	0.10	135.98	40.94	0.02	2.75	204.73
GHG (kg)	1.76	0.01	9.58	2.88	0.00	0.19	14.42
Operating Cost ($)	14.80	0.29	78.85	28.71	7.67	8.26	138.57
Waste (kg)	0.00	0.05	0.00	0.00	21.92	1.24	23.20
Lost Work Days (#)	4.44	0.22	22.56	11.28	1.37	0.38	40.24
Average Wage ($/hr)	25.00	25.00	25.00	25.00	25.00	25.00	25.00
OPTION 2	Anneal	Mill	Harden	Recover	Induction	Coat	Total
Energy (kWh)	24.94	0.10	135.98	40.94	13.80	2.75	218.51
GHG (kg)	1.76	0.01	9.58	2.88	0.97	0.19	15.40
Operating Cost ($)	14.80	0.29	78.85	28.71	5.62	8.26	136.52
Waste (kg)	0.00	0.05	0.00	0.00	0.00	1.24	1.28
Lost Work Days (#)	4.44	0.22	22.56	11.28	0.13	0.38	38.99
Average Wage ($/hr)	25.00	25.00	25.00	25.00	25.00	25.00	25.00

Summary

With the limitations of LCA methods and tools more widely known within the research field, and the steady push of industry for updated methods and tools capable of uncovering new opportunities for sustainable manufacturing improvement, the research field has focused more prominently on developing new methods and tools for UMP and manufacturing system assessment. To uncover new improvement opportunities requires methods that not only demonstrate improvements in UMP and system modeling accuracy, but are also implementable. To facilitate implementation requires models be written in a standardized format, and to improve system accuracy requires that UMP models be composed. Both of these needs were meet with the development of an information framework proposed in [215], and was used to scaffold the desktop application in this research The application facilitates sustainable assessments during the design for manufacturing phase.

The main shortcoming of this application resides within the chosen sustainability assessment method; sustainability metrics are not comparable against one another without some weighting scheme. This provides direction to future work. Weighting schemes have been developed to assist multicriteria decision making. Examples of multicriteria decision making approaches have been reported by Zhang and Haapala [225], Munda [226], and Qi et al. [227] for sustainability assessment. These authors provide methods for weighting metrics, but still rely on decision makers to assign the initial weights.

Other next steps include expanding the application's capacity to include assemblies and parallel processing of manufactured components. As it stands, the application assumes that all components follow a single process flow. Furthermore, the application could be extended to semi-automate the selection of subsequent processes by real-time consideration of alternatives and presentation of the superior process to the user. Incorporating this functionality could speed the decision-making process in design for manufacturing, and could also help direct continuous improvement events.

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CHAPTER 6: CONCLUSION

Sustainable manufacturing invokes the desire to produce clean, harmless products for the benefit of the environment and all stakeholders. Sustainability requires a new weltanschauung where stewardship becomes the driving ethos, and a "do no harm" mentality rules decision making. However, this weltanschauung (worldview) has proven fiendishly difficult to undertake and maintain. What is needed is research into methods in the design and manufacture of goods to sustain and advance the sustainability of manufacturing, for while improvements have been made, drastic changes are imperative. Sustainable manufacturing research is still within its infancy, and the optimistic individual and company holds the viewpoint that greater investment will yield drastic results. However, sustainability must compete with other short and long term goals and needs for this investment. To continue capturing the public's interest, sustainable manufacturing research must become industry practice. Thereafter the results can spark new research and become new practice in a virtuous cycle. It is imperative then, that this cycle not be broken. The use of standards and regulations is one of the strongest available methods to ensure that sustainability does not lose to other goals and needs and the virtuous cycle of research to practice continues unabated.

Thus, research demonstrating improvements to sustainable manufacturing process and system sustainability is fertile ground for translating into industry practice through standards adoption and general acceptance.

Summary

The research reported herein was undertaken to develop an information modeling framework to compose UMPs for manufacturing systems assessment. To produce products that improve all three aspects of sustainability: economic, environmental, and social, requires understanding and fully utilizing the information held within the manufacturing system used to produce the product. This research attempted to address this objective by gathering industry input on sustainable manufacturing needs, investigating composing UMPs to gain resolution on the requirements needed to successfully transfer information, and produce an XML Schema and accompany desktop application to structure, label, and assess composed manufacturing systems for sustainable assessment.

The need for an information framework for composed manufacturing systems was uncovered through literature review and input from industry roundtable meeting participants. The results of the literature review and the roundtable meetings have value beyond the research presented herein, as the results can be used to orient other areas of sustainability in line with industry and research needs. From there an information modeling framework was developed through review of past research in information modeling, and investigating representative composed manufacturing systems to provide clarity to what information is required to first compose UMPs, and then assess their sustainability performance. Derived from this framework was an XML Schema to structure and label the information within a manufacturing system for sustainable assessment. A result of structuring information using the XML Schema is the ability to then implement UMP and system sustainable assessment in a software application. The UMP and system models are constructed using the Schema, and the application then reads the information within the XML based models to produce a sustainability assessment.

Conclusions

Learnings from this research support UMP composability and information capture for sustainable assessment in several manners. 1) The group discussion from the roundtable meetings and accompanying literature reviews uncovered previously unknown deficits between industry and research body needs and reinforced known deficits in translating academic research to industry practice. 2) Composing UMPs for sustainable assessment was found to improve system modeling accuracy. 3) The investigation into composability uncovered the need and the material for the development of an information modeling framework to identify, trace, structure, and label the information within a composed manufacturing system for sustainable assessment. This information framework was realized in the form of an XML Schema. 4) With this framework and the implemented XML Schema, it became possible to develop a desktop software application to speed the composing and sustainable assessment of manufacturing systems. More on the research findings of this thesis are provided in the following paragraphs.

First, identifying the deficits in translating academic research to industry practice in Chapter 2 lead to the conclusion that more focus should be placed on improving the accuracy and clarity of manufacturing process and system models. This informed the research in this thesis towards creating information frameworks and accompanying tools ready for industry use.

Second, investigating the feasibility of composing UMPs in Chapter 3 confirmed the initial belief that composability would improve model predictive accuracy and provided the inspiration for an information framework. By composing two UMPs together and tracing the individual UMP transformations to a set of sustainability metrics, the information required to do such an assessment became apparent to the research team. Thus, it became apparent that in order to compose UMPs, the linking relationship between the two UMPs must be captured alongside the known UMP model information.

Third, the results of investigating composability lead to the reasoning that an information modeling framework is required to ensure that all UMPs and manufacturing systems are modeled to include the same information. This enables a composed UMP system to be shared and reused among different research and industry users, with the outcome being that sustainability advances can be disseminated more thoroughly through other bodies. The information framework deconstructs the flow of information between different objects within a composed system. The framework covers the flow of information within a UMP, between UMPs, and from UMPs to the associated sustainability metrics. The framework is realized in the form of an XML Schema. The Schema strictly dictates what information is to be captured and labeled for each UMP, its inputs, outputs, transformation, process and feedback information, and for the composing of one UMP to another. The composing element dictates tracing the flow of information from the downstream to the upstream UMP by decreeing the input and output variable from which the composing element pulls and pushes information from and to.

Fourth, the development of a desktop software application built upon the information framework lead to a better understanding of the strengths and weaknesses of the framework when used in an industry-like use scenario. While the application sped the development of composed manufacturing systems and their assessment, it was incapable of suggesting superior manufacturing flows or automating the population of manufacturing systems. Including this ability would dramatically reduce the effort required to produce superior manufacturing systems, by replacing manual construction of system models with automation, leaving engineers to focus on improving the sustainability performance of each constituent system UMP.

Contributions

The presented work contributed three tangible products.

Contribution 1: The input from industry participants gathered from the roundtable meetings and the survey clarified the deficit that exists between industry and academic research and the needs from industry to advance sustainable manufacturing practices. The result of this input took the form of a final barriers and recommendations table that condensed all input into a table of the top barriers and recommendations to a set of three topic questions. It is expected that this table will find use in future research projects.

Contribution 2: The information framework and accompanying XML Schema developed under this research will strongly aid researchers and industry practitioners in characterizing their manufacturing processes and systems in a standard manner. This will act to reduce the current ad hoc environment and will promote the sharing of well-made UMP models, improve UMP and system accuracy by streamlining composing, and set forth the foundation for a move into software aided sustainable production planning.

Contribution 3: A prototype software application was developed that built upon the information framework and aimed at addressing industry concerns that process modeling techniques have not been implemented in for use applications. This application will be of use within academic research and could act as a 1st generation prototype for the development of richer, more capable, commercializable software applications.

Opportunities for Future Research

There are several opportunities for future research in this area of interest. This thesis used industry input and literature review to strengthen the rationale behind the creation of an information modeling framework and accompanying software application. Within this research, assumptions were made that if further researched would strengthen this field of research. Furthermore, the research conducted herein uncovered new areas in need of investigation.

Opportunity 1: Within this research, an investigation into composability was done by linking Shot Peening to Spray Coating. The information gleaned from this investigation was incorporated into the information modeling framework. An opportunity exists to test the robustness of the framework by investigating more composed manufacturing systems. If the framework and the accompanying XML Schema are able to visualize and capture the information within other composed systems, then the framework is robust. Otherwise, investigating more cases of composed manufacturing systems provides the opportunity to uncover deficits in the framework that then be addressed. For example, the linking action taken to link Shot Peening to Spray Coating relied on using surface area as a common variable. It would be interesting to investigate the potential for other linking variables to act as information carriers. Finally, the models investigated to test composability remained theoretical, empirical validation would reinforce the findings from this research.

Opportunity 2: The XML Schema developed as part of the information framework and presented in Chapter 4 offers opportunities for improvement. The Schema as presented can only check for well-formed content. Meaning that the Schema can check the syntax of an instantiated XML document is properly formatted (e.g., no closing carrots or whitespace is missing) but cannot check for good content. However, this is a functionality that can be added to Schemas to expand their power and robustness. Future research should look towards adding these capabilities as a complement to the structure and data labeling elements already present within the application. Schema validation would look to validate structure, and content using conditional tests, structure assertions, and binomial presence of information assertions.

Opportunity 3: The software application developed as a proof-of-concept is designed for limited internal use by researchers well versed in UMP and composing UMP characterization. It requires manually selecting each UMP for linking to produce a manufacturing system capable of making a desired part. To expand the applications usefulness to both experts and not experts, the application could benefit from the addition of an element of intelligence, in that the application could automatically compare and select UMPs based on their sustainability, for placement in a linear manufacturing system. The application could then populate the most sustainable pathway for the manufacture of a product with little user intervention.

Last Remarks

This body of work makes incremental progress in understanding how manufacturing activities can be modeled and assessed. Better communication, assessments, and data organization for UMP modeling enables more informed decision making in engineering and management within industry and academia. Composing UMP models makes more complete manufacturing systems. And with the addition of an XML Schema and overlying information framework, will enable the advancement of computer-aided manufacturing

(CAM) through software to plan, assess, and optimize manufacturing systems for a sustainable world. Sustainable manufacturing could advance along many fronts, and must do. The work presented herein can enable advancement on one front into more detailed and accurate modeling of manufacturing processes and systems. With this research, increment improvements could happen within industry and as the adoption of UMP-based assessment methods and tools accelerates and achieves widespread use, then a more sustainable future can be realized.

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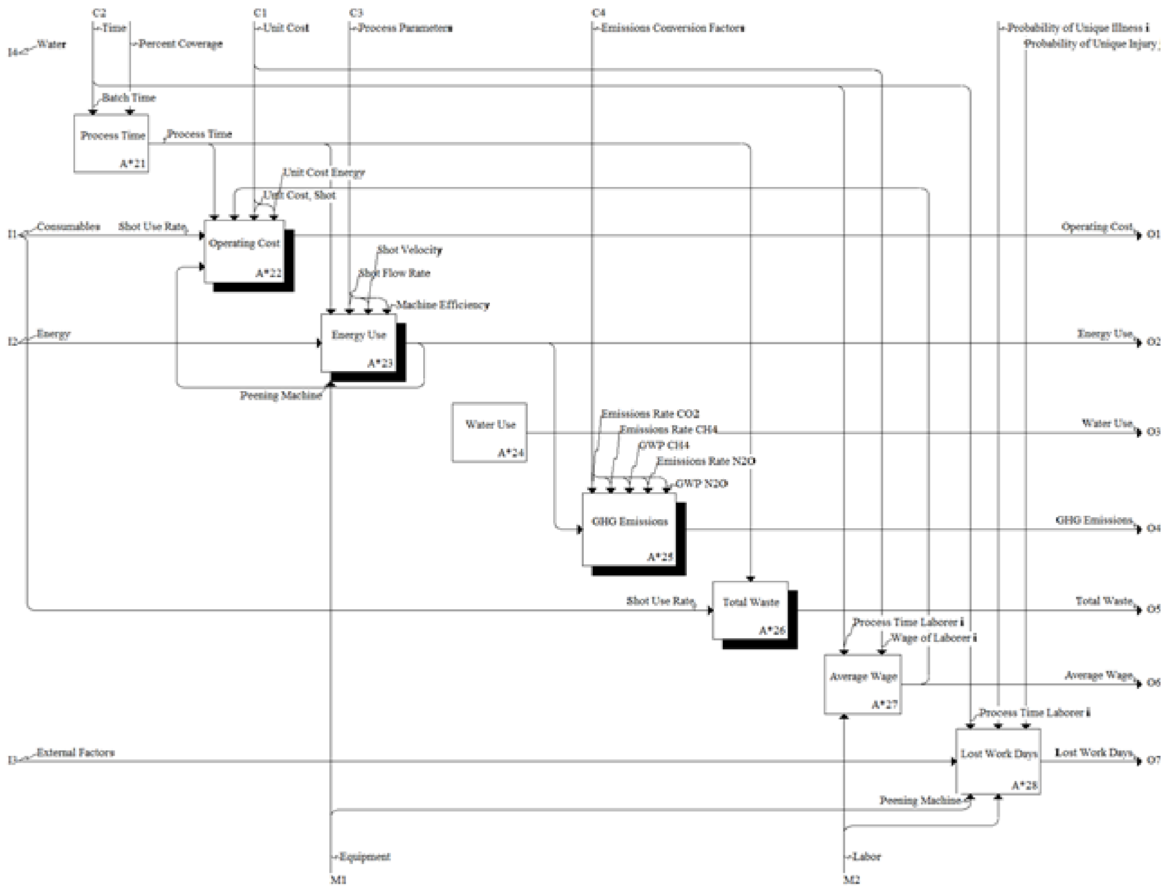
APPENDIX A: IDEF0 DIAGRAM OF THE INFORMATION FLOWS BETWEEN SUSTAINABLE ASESSMENT METRICS



APPENDIX B: XML SCHEMA FOR COMPOSED MANUFACTURING SYSTEMS

```
<xs:schema id="UMPSchema" xmlns=""
xmlns:xs="http://www.w3.org/2001/XMLSchema">

  <xs:element name="ComposedSystem">
    <xs:complexType>
      <xs:sequence>
        <xs:element name="Metadata">
  <xs:complexType>
    <xs:attribute name="modelName" type="xs:string"/>
    <xs:attribute name="author" type="xs:string"/>
    <xs:attribute name="institution" type="xs:string"/>
    <xs:attribute name="dateCreated" type="xs:string"/>
    <xs:attribute name="dateLastModified" type="xs:string"/>
  </xs:complexType>
</xs:element>
        <xs:element name="UMPs">
          <xs:complexType>
            <xs:sequence>
              <xs:element name="UMP" minOccurs="0" maxOccurs="unbounded">
                <xs:complexType>
                  <xs:sequence>
                    <xs:element name="Input" minOccurs="0"
maxOccurs="unbounded">
                      <xs:complexType>
                        <xs:attribute name="name" type="xs:string"/>
                        <xs:attribute name="description"
type="descriptiontype"/>
                        <xs:attribute name="category" type="categorytype"/>
                        <xs:attribute name=" type" type="datatype"/>
                        <xs:attribute name="value" type="xs:decimal"/>
                        <xs:attribute name="unit" type="unittype"/>
                      </xs:complexType>
                    </xs:element>
                    <xs:element name="Output" minOccurs="0"
maxOccurs="unbounded">
                      <xs:complexType>
                        <xs:attribute name="name" type="xs:string"/>
                        <xs:attribute name="description"
type="descriptiontype"/>
                        <xs:attribute name="category" type="categorytype"/>
                        <xs:attribute name=" type" type="datatype"/>
                        <xs:attribute name="value" type="xs:decimal"/>
                        <xs:attribute name="unit" type="unittype"/>
                      </xs:complexType>
                    </xs:element>
                    <xs:element name="Feedback" minOccurs="0"
maxOccurs="unbounded">
                      <xs:complexType>
                        <xs:attribute name="name" type="xs:string"/>
                        <xs:attribute name="description"
type="descriptiontype"/>
                        <xs:attribute name="value" type="xs:decimal"/>
                        <xs:attribute name="unit" type="unittype"/>
                      </xs:complexType>
```

```
                    </xs:element>
                    <xs:element name="ProductProcessInformation"
minOccurs="0" maxOccurs="unbounded">
                      <xs:complexType>
                        <xs:attribute name="name" type="xs:string"/>
                        <xs:attribute name="description"
type="descriptiontype"/>
                        <xs:attribute name="category" type="categorytype"/>
                        <xs:attribute name="value" type="xs:decimal"/>
                        <xs:attribute name="unit" type="unittype"/>
                      </xs:complexType>
                    </xs:element>
                    <xs:element name="ResourceInformation" minOccurs="0"
maxOccurs="unbounded">
                      <xs:complexType>
                        <xs:attribute name="name" type="xs:string"/>
                        <xs:attribute name="description"
type="descriptiontype"/>
                        <xs:attribute name="category" type="categorytype"/>
                        <xs:attribute name="value" type="xs:decimal"/>
                        <xs:attribute name="unit" type="unittype"/>
                      </xs:complexType>
                    </xs:element>
                    <xs:element name="Transformation" minOccurs="0"
maxOccurs="1">
                      <xs:complexType>
                        <xs:sequence>
                          <xs:element name="Equation" minOccurs="0"
maxOccurs="unbounded">
                            <xs:complexType>
                              <xs:simpleContent>
                                <xs:extension base="xs:string">
                                  <xs:attribute name="category"
type="categorytype"/>
                                  <xs:attribute name="description"
type="descriptiontype"/>
                                  <xs:attribute name="set" type="xs:string"/>
                                </xs:extension>
                              </xs:simpleContent>
                            </xs:complexType>
                          </xs:element>
                        </xs:sequence>
                      </xs:complexType>
                    </xs:element>
                  </xs:sequence>
                  <xs:attribute name="name" type="xs:string"/>
                  <xs:attribute name="type" type="datatype"/>
                  <xs:attribute name="description" type="descriptiontype"/>
```

```
                </xs:complexType>
              </xs:element>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
        <xs:element name="Linking">
          <xs:complexType>
            <xs:sequence>
              <xs:element name="LinkingAction" minOccurs="0" maxOccurs="1">
                <xs:complexType>
                  <xs:attribute name="targetUMP" type="xs:string"/>
                  <xs:attribute name="sourceUMP" type="xs:string"/>
                  <xs:attribute name="description" type="descriptiontype"/>
                </xs:complexType>
              </xs:element>
              <xs:element name="Transformation" minOccurs="0"
maxOccurs="unbounded">
                <xs:complexType>
                  <xs:sequence>
                    <xs:element name="Equation" minOccurs="0"
maxOccurs="unbounded">
                      <xs:complexType>

                        <xs:attribute name="description" type="xs:string"/>
                      </xs:complexType>
                    </xs:element>
                    <xs:element name="EquationVariables" minOccurs="0"
maxOccurs="unbounded">

                      <xs:complexType>
                        <xs:attribute name="description"
type="descriptiontype"/>
                        <xs:attribute name="category" type="categorytype"/>
                        <xs:attribute name="set" type="xs:string"/>
                        <xs:attribute name="origin" type="xs:string"/> <!--
whether its found from the sourceUMP, the target UMP, or the workpiece-->
                      </xs:complexType>
                    </xs:element>
                  </xs:sequence>
                  <xs:attribute name="targetInput" type="xs:string"/>
                  <xs:attribute name="sourceOutput" type="xs:string"/>
                  <xs:attribute name="description" type="descriptiontype"/>
                </xs:complexType>
              </xs:element>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:sequence>
    </xs:complexType>
  </xs:element>
    <xs:simpleType name="categorytype">
      <xs:restriction base="xs:string"/>
    </xs:simpleType>
```

```
    <xs:simpleType name="descriptiontype">
      <xs:restriction base="xs:string"/>
    </xs:simpleType>
    <xs:simpleType name="datatype">
      <xs:restriction base="xs:string"/>
    </xs:simpleType>
    <xs:simpleType name="unittype">
      <xs:restriction base="xs:string"/>
    </xs:simpleType>
</xs:schema>
```

APPENDIX C: XML SOURCE CODE FOR OPTION 1 IN CHAPTER 5 TO PRODUCE AN AUTOMOBILE-LIKE PART


```xml
<ComposedSystem>
  <UMPs>
    <UMP name="Annealing" type="Structure Modification" description="Heating
and Cooling of the workpiece">
      <Input name="Natural Gas" description="mass of natural gas provided to
provide required heat" category="Consumable" type="Energy" value="" unit="kg"
/>
      <Input name="Oxygen" description="mass of oxygen provided for
combustion" category="Consumable" type="Atmosphere" value="" unit="kg" />
      <Output name="Flue Gas" description="emissions from combustion"
category="GHG Emissions" type="Hazards" value="" unit="cfm" />
      <Output name="Total Heat loss" description="heat lossed to convection
and conduction" category="Energy" type="Heat" value="" unit="KJ/sec" />
      <Output name="Yield Strength" description="target yield strength of the
workpiece" category="Information" type="workpiece" value="300" unit="MPa" />
      <Output name="Energy Consumed" description="total energy consumed by
the process" category="Energy" type="Electricity" value="" unit="KwH" />
      <Output name="Process Time" description="total elapsed time to heat and
cool workpiece" category="Information" type="process" value="" unit="min" />
      <Feedback name="Mass of Natural Gas Burned" description="" value=""
unit="Kg" />
      <Feedback name="Time to Burn one kg CH4" description="" value="-"
unit="min" />
      <Feedback name="Mass Flow Rate of Flue Gas" description="" value=""
unit="cfm" />
      <Feedback name="Percent Excess Air" description="percent excess after
combustion" value="" unit="%" />
      <Feedback name="Density of Flue Gas" description="" value=""
unit="kg/m^3" />
      <Feedback name="Heat Lost From Oven" description="due to wall
conduction and convection" value="" unit="KJ/sec" />
      <Feedback name="Heat Carried off by Workpiece"
description="description3" value="" unit="KJ/sec" />
      <ProductProcessInformation category="" description="description1"
name="Heat Transfer Oven Wall" value="1"
unit="">k</ProductProcessInformation>
      <ProductProcessInformation category="" description="description2"
name="Oven Wall Thickness" value="-" unit="" >t</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description3"
name="Surface Area of Workpiece" value="" unit=""
>As</ProductProcessInformation>
      <ProductProcessInformation category="" description="description4"
name="Ambient Temperature" value="" unit=""
>Troom</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description4"
name="Starting Oven Temperature" value="" unit=""
>Toven</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description4" name="Workpiece Heat
Capacity" value="" unit="" >cp</ProductProcessInformation>
      <ProductProcessInformation category="" description="description4" name="Workpiece Mass"
value="" unit="" >mpart</ProductProcessInformation>
      <ResourceInformation category="Consumables" name="Mass Stoichiometric Air" description=""
value="" unit="" >Mair</ResourceInformation>
```

```
      <ResourceInformation category="Consumables" name="Enthalpy of
Combustion for Natural Gas" description="" value="" unit=""
>deltaCHCH4</ResourceInformation>
      <Transformation>
        <Equation category="Energy" description="heat lost from oven
conduction"
set="Heat">ovenHeatLoss=heatTransferOvenWall*surfaceArea*(tempOven-
tempRoomAmbient)/wallThickness</Equation>
        <Equation category="Energy" description="mass flow rate of flue gas"
set="Heat">massFlowRateFlueGas=flowRate*densityFlueGas</Equation>
        <Equation category="Time" description="time to burn one Kg CH4"
set="Heat">burnTime=(massCombustAir+massCombustCH4)/massFlowRateFlueGas</Equa
tion>
        <Equation category="Energy" description="total heat lost in flue gas
" set="Heat">flueGasHeatLoss=(tempFlueDown-
tempRoomAmbient)*(massCombustAir+massCombustCH4)*(specHeatFlueGas/burnTime)</
Equation>
        <Equation category="Energy" description="total heat loss"
set="Heat">totalHeat=ovenHeatLoss+flueGasHeatLoss</Equation>
        <Equation category="Energy" description="total energy required"
set="Heat">energyReqd=totalHeat*processTime</Equation>
        <!--Equation category="Energy" description="describes the total
natural gas burned " set="Natural
Gas">massCH4burned=(enthalpyCombustCHCH4/energyReqd)/(1-
percUncombusted)</Equation-->
        <!--Equation category="Percent" description="percent heat lost in
flue gas"
set="Heat">percFlueGasLoss=flueGasHeatLoss/enthalpyCombustCHCH4</Equation-->
        <!--Equation category="Percent" description="percent excess air"
set="Heat">percExcessAir=(percO2FlueGas/(21-percO2FlueGas))*100</Equation-->
        <!--Equation category="Energy" description="total air supplied to
oven" set="Heat">massAir=massStoicAir*(1+percExcessAir/100)</Equation-->
        <!--Equation category="Energy" description="heat lost to Workpiece"
set="Heat">workpieceHeatLoss =workpieceHeatCapacity*massPart*(tempOven-
tempRoomAmbient)</Equation-->
      </Transformation>
    </UMP>

    <UMP name="Milling" type="Material Removal" description="">
      <Input name="Coolant"></Input>
      <Input name="Energy"></Input>
      <Output name="Waste"></Output>
      <Feedback name="Tank Volume Full"></Feedback>
      <Feedback name="Tank Volume Low"></Feedback>
      <Feedback name="Tank Refill Rate"></Feedback>
      <Feedback name="Process Time"></Feedback>
      <ProductProcessInformation name="Quenchant
Concentration"></ProductProcessInformation>
      <ResourceInformation name="Power Efficiency">powerEfficiency</ResourceInformation>
    <Transformation>
      <Equation>volRemoved=volInitial-volFinal</Equation>
      <Equation>matRemoved=volRemoved*matDensity*unitConversion</Equation>
      <Equation>volCoolant=volTank*coolantConc</Equation>
```

```
      <Equation>volWater=volTank*coolantConc</Equation>
        <Equation>volCoolantUsed =
coolantConc*tankDischarged*cuttingTime/timeInterval</Equation>

<Equation>massCoolantUsed=volCoolantUsed*coolantDensity*massConversion</Equat
ion>
        <Equation>feedRate=feed*teeth*spindleSpeed</Equation>
        <Equation>MRR=feedRate*widthCut*depthCut</Equation>
        <Equation>feedFactor=0.417*feed^-0.197</Equation>

<Equation>powerCuttingTool=powerConstant*feedFactor*MRR*toolWear</Equation>
        <Equation>powerMotor=powerCuttingTool*machineEff</Equation>
        <Equation>cuttingTime=volRemoved/MRR/60</Equation>
        <!--Equation>idlePower=powerMotor*idlePowerFactor</Equation>
        <Equation>idleTime=airTime+cuttingTime</Equation>
        <Equation>basicPower=idlePower*basicPowerFactor</Equation>
        <Equation>basicTime=setupTime+idleTime</Equation-->

<Equation>energyConsumption=(powerMotor*cuttingTime+idlePower*idleTime+basicP
ower*basicTime)/.7457</Equation>
      </Transformation>
    </UMP>

    <UMP name="Through Hardening" type="Structure Modification"
description="">
      <Input name="Natural Gas" description="mass of natural gas provided to
provide required heat" category="Consumable" type="Energy" value="" unit="kg"
/>
      <Input name="Oxygen" description="mass of oxygen provided for
combustion" category="Consumable" type="Atmosphere" value="" unit="kg" />
      <Output name="Flue Gas" description="emissions from combustion"
category="GHG Emissions" type="Hazards" value="" unit="cfm" />
      <Output name="Total Heat loss" description="heat lossed to convection
and conduction" category="Energy" type="Heat" value="" unit="KJ/sec" />
      <Output name="Yield Strength" description="target yield strength of the
workpiece" category="Information" type="workpiece" value="300" unit="MPa" />
      <Output name="Energy Consumed" description="total energy consumed by
the process" category="Energy" type="Electricity" value="" unit="KwH" />
      <Output name="Process Time" description="total elapsed time to heat and
cool workpiece" category="Information" type="process" value="" unit="min" />
      <Feedback name="Mass of Natural Gas Burned" description="" value=""
unit="Kg" />
      <Feedback name="Time to Burn one kg CH4" description="" value="-"
unit="min" />
      <Feedback name="Mass Flow Rate of Flue Gas" description="" value=""
unit="cfm" />
      <Feedback name="Percent Excess Air" description="percent excess after
combustion" value="" unit="%" />
```

```
      <Feedback name="Density of Flue Gas" description="" value=""
unit="kg/m^3" />
      <Feedback name="Heat Lost From Oven" description="due to wall
conduction and convection" value="" unit="KJ/sec" />
      <Feedback name="Heat Carried off by Workpiece"
description="description3" value="" unit="KJ/sec" />
      <ProductProcessInformation category="" description="description1"
name="Heat Transfer Oven Wall" value="1"
unit="">k</ProductProcessInformation>
      <ProductProcessInformation category="" description="description2"
name="Oven Wall Thickness" value="-" unit="" >t</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description3"
name="Surface Area of Workpiece" value="" unit=""
>As</ProductProcessInformation>
      <ProductProcessInformation category="" description="description4"
name="Ambient Temperature" value="" unit=""
>Troom</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description4"
name="Starting Oven Temperature" value="" unit=""
>Toven</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description4"
name="Workpiece Heat Capacity" value="" unit=""
>cp</ProductProcessInformation>
      <ProductProcessInformation category="" description="description4"
name="Workpiece Mass" value="" unit="" >mpart</ProductProcessInformation>
      <ResourceInformation category="Consumables" name="Mass Stoichiometric
Air" description="" value="" unit="" >Mair</ResourceInformation>
      <ResourceInformation category="Consumables" name="Enthalpy of
Combustion for Natural Gas" description="" value="" unit=""
>deltaCHCH4</ResourceInformation>
      <Transformation>
        <Equation category="Energy" description="heat lost from oven
conduction"
set="Heat">ovenHeatLoss=heatTransferOvenWall*surfaceArea*(tempOven-
tempRoomAmbient)/wallThickness</Equation>
        <Equation category="Energy" description="mass flow rate of flue gas"
set="Heat">massFlowRateFlueGas=flowRate*densityFlueGas</Equation>
        <Equation category="Time" description="time to burn one Kg CH4"
set="Heat">burnTime=(massCombustAir+massCombustCH4)/massFlowRateFlueGas</Equa
tion>
        <Equation category="Energy" description="total heat lost in flue gas
" set="Heat">flueGasHeatLoss=(tempFlueDown -
tempRoomAmbient)*(massCombustAir+massCombustCH4)*(specHeatFlueGas/burnTime)</
Equation>
        <Equation category="Energy" description="total heat loss"
set="Heat">totalHeat=ovenHeatLoss+flueGasHeatLoss</Equation>
        <Equation category="Energy" description="total energy required"
set="Heat">energyReqd=totalHeat*processTime</Equation>
        <Equation category="Energy" description="heat lost to Workpiece"
set="Heat">workpieceHeatLoss =workpieceHeatCapacity*massPart*(tempOven-
tempRoomAmbient)</Equation>
        <!--Equation category="Energy" description="describes the total
natural gas burned " set="Natural
Gas">massCH4burned=(enthalpyCombustCHCH4/energyReqd)/(1-
```

```
set="Heat">massAir=massStoicAir*(1+percExcessAir/100)</Equation-->
      </Transformation>
    </UMP>

    <UMP name="Recovery Anneal" type="Structure Modification" description="">
      <Input name=""/>
      <Input name=""/>
      <Output name=""/>
      <Feedback name="Process Time">processtime</Feedback>
      <ProductProcessInformation name=""/>
      <ResourceInformation name="" ></ResourceInformation>
      <Transformation>
      <Equation category="Energy" description="heat lost from oven
conduction"
set="Heat">ovenHeatLoss=heatTransferOvenWall*surfaceArea*(tempOven-
tempRoomAmbient)/wallThickness</Equation>
      <Equation category="Energy" description="mass flow rate of flue gas"
set="Heat">massFlowRateFlueGas=flowRate*densityFlueGas</Equation>
      <Equation category="Time" description="time to burn one Kg CH4"
set="Heat">burnTime=(massCombustAir+massCombustCH4)/massFlowRateFlueGas</Equa
tion>
      <Equation category="Energy" description="total heat lost in flue gas "
set="Heat">flueGasHeatLoss
=(tempFlueDown -
tempRoomAmbient)*(massCombustAir+massCombustCH4)*(specHeatFlueGas/burnTime)</
Equation>
      <Equation category="Energy" description="total heat loss"
set="Heat">totalHeat=ovenHeatLoss+flueGasHeatLoss</Equation>
      <Equation category="Energy" description="total energy required"
set="Heat">energyReqd=totalHeat*processTime</Equation>
      <Equation category="Energy" description="describes the total natural
gas burned " set="Natural
Gas">massCH4burned=(enthalpyCombustCHCH4/energyReqd)/(1-
percUncombusted)</Equation>
      <Equation category="Percent" description="percent heat lost in flue
gas"
set="Heat">percFlueGasLoss=flueGasHeatLoss/enthalpyCombustCHCH4</Equation>
      <Equation category="Percent" description="percent excess air"
set="Heat">percExcessAir=(percO2FlueGas/(21-percO2FlueGas))*100</Equation>
      <Equation category="Energy" description="total air supplied to oven"
set="Heat">massAir=massStoicAir*(1+percExcessAir/100)</Equation>
      <Equation category="Energy" description="heat lost to Workpiece"
set="Heat">workpieceHeatLoss =workpieceHeatCapacity*massPart*(tempOven-
tempRoomAmbient)</Equation>
      <Equation>processTime=t_cooling</Equation>
      <Equation>WP_UTS = -99.8+3.734*WPHardness</Equation>
      </Transformation>
    </UMP>

  </UMPs>
```

```
  <Linking>
    <LinkingAction targetUMP="Milling" sourceUMP="Annealing"
description=""/>
    <Transformation targetInput="UTS" sourceOutput="Vicker's Hardness">
      <!--Equation>WP_UTS = -99.8+3.734*WPHardness</Equation--> <!--removed
in favor of the MATLAB model written by Ian, we run his model and manually
enter results into the Composability tool-->
      <!--MPa-->
      <!--Equation>Final_WP_UTS = WP_UTS*10^6</Equation-->
      <!--Pa; [Pavlina and Van Tyne 2008]-->
    </Transformation>

    <LinkingAction targetUMP="Through Hardening" sourceUMP="Milling"
description="">
    <Transformation targetInput="Thickness"  sourceOutput="Thickness">
      <Equation>processTime =60*60*WPThickness</Equation>
      <!--Equation>Cutting_Energy_Incremental.m</Equation> calls a matlab
function to calculate the energy required to mill the workpiece-->
    </Transformation>
    </LinkingAction>

    <LinkingAction targetUMP="Recovery Anneal" sourceUMP="Through Hardening"
description="">
    <Transformation targetInput="Process Time" sourceOutput="Oven
Temperature">
      <Equation>t_Cooling = (Temp_Oven-Temp_Quench)/Cooling_Rate</Equation>
    </Transformation>
    </LinkingAction>

    <LinkingAction targetUMP="Recovery Anneal" sourceUMP="Through Hardening"
description="">
    <Transformation targetInput="Ultimate Tensile Strength"
sourceOutput="Oven Temperature">
      <Equation>t_Cooling=(Temp_Oven-Temp_Quench)/Cooling_Rate</Equation>
      <Equation>T=Temp_Oven</Equation>

      <!--Equation>HT_CL_Hard.m</Equation> calls a matlab equation to
calculate the change in strength; integral function-->
    </Transformation>
    </LinkingAction>
  </Linking>
</ComposedSystem>
```

```
<ComposedSystem>
  <UMPs>
    <UMP name="Recovery Anneal" type="Structure Modification"
description="Cooling of the workpiece">
      <Input name="Natural Gas" description="mass of natural gas provided to
provide required heat" category="Consumable" type="Energy" value="" unit="kg"
/>
      <Input name="Oxygen" description="mass of oxygen provided for
combustion" category="Consumable" type="Atmosphere" value="" unit="kg" />
      <Output name="Flue Gas" description="emissions from combustion"
category="GHG Emissions" type="Hazards" value="" unit="cfm" />
      <Output name="Total Heat loss" description="heat lossed to convection
and conduction" category="Energy" type="Heat" value="" unit="KJ/sec" />
      <Output name="Yield Strength" description="target yield strength of the
workpiece" category="Information" type="workpiece" value="300" unit="MPa" />
      <Output name="Energy Consumed" description="total energy consumed by
the process" category="Energy" type="Electricity" value="" unit="KwH" />
      <Output name="Process Time" description="total elapsed time to heat and
cool workpiece" category="Information" type="process" value="" unit="min" />
      <Feedback name="Mass of Natural Gas Burned" description="" value=""
unit="Kg" />
      <Feedback name="Time to Burn one kg CH4" description="" value="-"
unit="min" />
      <Feedback name="Mass Flow Rate of Flue Gas" description="" value=""
unit="cfm" />
      <Feedback name="Percent Excess Air" description="percent excess after
combustion" value="" unit="%" />
      <Feedback name="Density of Flue Gas" description="" value=""
unit="kg/m^3" />
      <Feedback name="Heat Lost From Oven" description="due to wall
conduction and convection" value="" unit="KJ/sec" />
      <Feedback name="Heat Carried off by Workpiece"
description="description3" value="" unit="KJ/sec" />
      <ProductProcessInformation category="" description="description1"
name="Heat Transfer Oven Wall" value="1"
unit="">k</ProductProcessInformation>
      <ProductProcessInformation category="" description="description2"
name="Oven Wall Thickness" value="-" unit="" >t</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description3"
name="Surface Area of Workpiece" value="" unit=""
>As</ProductProcessInformation>
      <ProductProcessInformation category="" description="description4"
name="Ambient Temperature" value="" unit=""
>Troom</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description4"
name="Starting Oven Temperature" value="" unit=""
>Toven</ProductProcessInformation>>
      <ProductProcessInformation category="" description="description4"
name="Workpiece Heat Capacity" value="" unit=""
>cp</ProductProcessInformation>
```

```
      <ProductProcessInformation category="" description="description4"
name="Workpiece Mass" value="" unit="" >mpart</ProductProcessInformation>
      <ResourceInformation category="Consumables" name="Mass Stoichiometric
Air" description="" value="" unit="" >Mair</ResourceInformation>
      <ResourceInformation category="Consumables" name="Enthalpy of
Combustion for Natural Gas" description="" value="" unit=""
>deltaCHCH4</ResourceInformation>
      <Transformation>
        <Equation category="Energy" description="heat lost from oven
conduction"
set="Heat">ovenHeatLoss=heatTransferOvenWall*surfaceArea*(tempOven-
tempRoomAmbient)/wallThickness</Equation>
        <Equation category="Energy" description="mass flow rate of flue gas"
set="Heat">massFlowRateFlueGas=flowRate*densityFlueGas</Equation>
        <Equation category="Time" description="time to burn one Kg CH4"
set="Heat">burnTime=(massCombustAir+massCombustCH4)/massFlowRateFlueGas</Equa
tion>
        <Equation category="Energy" description="total heat lost in flue gas
" set="Heat">flueGasHeatLoss=(tempFlueDown -
tempRoomAmbient)*(massCombustAir+massCombustCH4)*(specHeatFlueGas/burnTime)</
Equation>
        <Equation category="Energy" description="total heat loss"
set="Heat">totalHeat=ovenHeatLoss+flueGasHeatLoss</Equation>
        <Equation category="Energy" description="total energy required"
set="Heat">energyReqd=totalHeat*processTime</Equation>
        <Equation category="Energy" description="describes the total natural
gas burned " set="Natural
Gas">massCH4burned=(enthalpyCombustCHCH4/energyReqd)/(1-
percUncombusted)</Equation>
        <Equation category="Percent" description="percent heat lost in flue
gas"
set="Heat">percFlueGasLoss=flueGasHeatLoss/enthalpyCombustCHCH4</Equation>
        <Equation category="Percent" description="percent excess air"
set="Heat">percExcessAir=(percO2FlueGas/(21-percO2FlueGas))*100</Equation>
        <Equation category="Energy" description="total air supplied to oven"
set="Heat">massAir=massStoicAir*(1+percExcessAir/100)</Equation>
        <Equation category="Energy" description="heat lost to Workpiece"
set="Heat">workpieceHeatLoss =workpieceHeatCapacity*massPart*(tempOven-
tempRoomAmbient)</Equation>
      </Transformation>
    </UMP>
    <UMP name="Induction Hardening" type="Structure Modification"
description="">
      <Input name="Quenchant" description="description1" category="category1"
type="type1" value="1" unit="unit1" />
      <Input name="Energy" description="description2" category="category2"
type="type2" value="-79228162514264337593543950335" unit="unit2" />
      <Output name="Waste Fluid" description="description1"
category="category1" type="type1" value="1" unit="unit1" />

      <Feedback name="Tank Volume Full"/>
      <Feedback name="Tank Volume Low"/>
      <Feedback name="Tank Refill Rate"/>
      <Feedback name="Process Time"/>
```

```
      <ProductProcessInformation name="Quenchant Concentration"/>
      <ProductProcessInformation name="Generator Power"/>
      <ProductProcessInformation name="Percent High Frequency"/>
      <ProductProcessInformation name="Percent Medium Frequency"/>
      <ProductProcessInformation name="Coil Resistance"/>
      <ProductProcessInformation name="Coil Current High Frequency"/>
      <ProductProcessInformation name="Coil Current Medium Frequency"/>
      <ProductProcessInformation name="Initial Workpiece Resistance"/>
      <ProductProcessInformation name="Heat Temperature"/>
      <ProductProcessInformation name="Ambient Temperature"/>
      <ProductProcessInformation name="Magnetic Permeability"/>
      <ProductProcessInformation name="Surface Area Topland"/>
      <ProductProcessInformation name="Surface Area Gear Root"/>
      <ProductProcessInformation name="Teeth"/>
      <ProductProcessInformation name="Area Conversion"/>
      <ProductProcessInformation name="Topland Angle"/>
      <ProductProcessInformation name="Gear Root Angle"/>
      <ProductProcessInformation name="Surface Area Gear Root"/>

      <Transformation>
        <Equation>volWaterLost = (100-quenchantConc)*(tankVol-
tankVolLow)*(processTime/tankRefillInterval)</Equation>
        <Equation>volQuenchantLost = quenchantConc*(tankVol-
tankVolLow)*(processTime/tankRefillInterval)</Equation>

<Equation>massQuenchantLost=volQuenchantLost/quenchantDensity</Equation>
        <Equation>powerCoilHF =
generatorPower*percHF*powerEfficiency</Equation>
        <Equation>powerCoilMF =
generatorPower*percMF*powerEfficiency</Equation>
        <Equation>coilResistance =
resistivity*(2*3.14*coilRadius/coilCrossSectionArea)</Equation>
        <Equation>coilCurrentHF = (powerHF/coilResistance)^0.5</Equation>
        <Equation>coilCurrentMF = (powerMF/coilResistance)^0.5</Equation>
        <Equation>subVar_t =
(currentHF*coilRadius^2)/(2*distanceTopland^3)</Equation>
        <Equation>subVar_r =
(currentMF*coilRadius^2)/(2*distanceRoot^3)</Equation>
        <Equation>resistanceWP = initialResWP*(1+tempCoef(heatTemp-
ambientTemp))</Equation>
        <Equation>frequencyHF =
resistanceWP/(magPerm*(depthRoot/(1.6*503))^2)</Equation>
        <Equation>frequencyMF =
resistanceWP/(magPerm*(depthTopland/(1.6*503))^2)</Equation>
        <Equation>areaSurfaceHardTopland =
surfaceAreaTopland*numberTeeth*areaConversion</Equation>
        <Equation>areaSurfaceHardGearRoot =
surfaceAreaGearRoot*numberTeeth*areaConversion</Equation>
        <Equation>magIntensityTopland =
(subvar_t^2*cos^2(angleTopland)*(0.25*sin^2(angleTopland)+1)+0.25*sin^4(angle
Topland))^0.5</Equation>
```

```
        <Equation>magIntensityGearRoot =
(subvar_t^2*cos^2(angleRoot)*(0.25*sin^2(angleRoot)+1)+0.25*sin^4(angleroot))
^0.5</Equation>
        <Equation>surfacePowerDensityTopland =
magIntensityTopland^2*(3.14*resistanceWP*magPerm*frequencyHF)^0.5</Equation>
        <Equation>surfacePowerDensityGearRoot =
magIntensityGearRoot^2*(3.14*resistanceWP*magPerm*frequencyMF)^0.5</Equation>
        <Equation>powerWP =
areaSurfaceHardTopland*surfacePowerDensityTopland+areaSurfaceHardGearRoot*sur
facePowerDensityGearRoot</Equation>
        <Equation>powerConsumptionPumps =
(quenchPump+wastefluidPump+coolingPump+highpressurePump)/(quenchEff+wasteflui
dEff+coolingEff+highpressureEff)*quenchduration*conversion</Equation>
        <Equation>totalEnergyConsumption =
powerWP*processTime+powerConsumptionPumps</Equation>
      </Transformation>
    </UMP>
      <ResourceInformation name="Power
Efficiency">powerEfficiency</ResourceInformation>
      <ResourceInformation
name="Resistivity">resistivity</ResourceInformation>
      <ResourceInformation name="Coil
Radius">coilRadius</ResourceInformation>
      <ResourceInformation name="Coil
Resistance">coilResistance</ResourceInformation>
      <ResourceInformation name="Coil Cross Sectional Area"/>
      <ResourceInformation name="Temperature Coefficient"/>
      <ResourceInformation name="Distance to Topland"/>
      <ResourceInformation name="Distance to Gear Root"/>
      <ResourceInformation name="Topland Depth"/>
      <ResourceInformation name="Gear Root Depth"/>
      <ResourceInformation name="Magnetic Intensity Topland"/>
      <ResourceInformation name="Magnetic Intensity Topland"/>
    <UMP name="Liquid Spray Coating" type="Surface Finishing" description="">
      <Input name="Paint"/>
      <Input name="Compressed Air"/>
      <Output name="Overspray"/>
      <Output name="Volume of Air Consumed"/>
      <Output name="Volume of Paint Consumed"/>
      <Feedback name="Process Time" description="description4" value="0.9"
unit="unit4" />
      <ProductProcessInformation name="Overspray Margin"/>
      <ProductProcessInformation name="Rated Tool Paint Flow"/>
      <ProductProcessInformation name="Power of Air Compressor"/>
      <ProductProcessInformation name="Number of Layers"/>
      <ProductProcessInformation name="Layer Thickness"/>
      <ProductProcessInformation name="Surface Area"/>
      <ResourceInformation name="Paint Density"/>
      <ResourceInformation name="Air Compressor Efficiency"/>
      <Transformation>
        <Equation category
```

```
="" description="description4"
set="set4">volumeAirConsumed=toolPaintFlow*processTime</Equation>
        <Equation category="category5" description="description5"
set="set5">volumePaintConsumed=layers*surfaceArea*layerThickness</Equation>
        <Equation category="category6" description="description6"
set="set6">energyCoat=volumeAirConsumed*powerAirCompressor/60</Equation>
        <Equation category="category6" description="description6"
set="set6">massPaintConsumed=volumePaintConsumed/paintDensity</Equation>
      </Transformation>
    </UMP>
  </UMPs>
  <Linking>
    <LinkingAction targetUMP="Induction Hardening"  sourceUMP="Recovery
Anneal" description="">
      <Transformation targetInput="Surface Area Topland"
sourceOutput="Surface Area">
        <!--
>Equation>pressureAngleOutside=invcos(pitchDiameter*cos(pressureAngle))/pitch
Diameter+2*module)</Equation-->
        <!--
Equation>theta=3.14/(2*teeth)+(2*undercut*tan(pressureAngle)/teeth+(inv(press
ureAngle)-inv(pressureAngleOutside))</Equation-->
        <!--
>Equation>surfaceAreaTopland=theta*(pitchDiameter+2*module</Equation-->
        <Equation>surfaceAreaTopland=surfaceArea-surfaceareaHoles-
surfaceAreaPocket</Equation>
      </Transformation>
    </LinkingAction>
    <LinkingAction targetUMP="Liquid Spray Coating" sourceUMP="Induction
Hardening" >
      <Transformation targetInput="Surface Area" sourceOutput="Surface Area">
        <!--
Equation>surfaceArea=areaSurfaceHardTopland+areaSurfaceHardGearRoot+(3.14*(pi
tchDiameter*cos(pressureAngle)/2+teeth*((distanceTopland+distanceGearRoot*(2.
2/pitchDiameter))/2)
        </Equation-->
        <Equation>surfaceArea=surfaceAreaTopland</Equation>
      </Transformation>
    </LinkingAction>
  </Linking>
</ComposedSystem>
```

APPENDIX D: XML SOURCE CODE FOR OPTION 2 THE ALTERNATE MANUFACTURING SYSTEM FOR AN AUTOMOBILE-LIKE PART

NOTE: To eliminate redundancy, only the replacement code is shown hereafter for the action of substituting induction hardening for shot peening in Appendix C Source Code

```
<ComposedSystem>
  <UMPs>

    <UMP name="Shot Peening" type="Surface Modification" description="imparts
a compressive residual stress to the surface of the workpiece through
bombardment with high velocity shot">
      <Input name="Shot" description="circular pellets of optional material"
category="Consumables" type="steel" value="" unit="Kg" />
      <Input name="Power" description="electrical energy to power process
machinery" category="Consumables" type="electrical" value="" unit="Kw" />
      <Input name="Coverage" description="Coverage required to achieve a
compressive stress" category="Information" type="workpiece" value="1.1"
unit="%" />
      <Output name="Spent Shot" description="spent shot unsuitable for reuse"
category="Waste" type="process" value="" unit="Kg" />
      <Output name="Process Time" description="time to peen a work surface to
preset " category="Information" type="process" value="" unit="min" />
      <Output name="Workpiece Surface Area" description="the surface area of
the workpiece after peening" category="Information" type="workpiece" value=""
unit="m^3" />
      <Output name="Workpiece Compressive Stress" description="compressive
stress imparted to work surface by peening" category="Information"
type="workpiece" value="" unit="MPa" />
      <Feedback name="shot use rate" description="" value="" unit="Kg/sec"
>shotUseRate</Feedback>
      <Feedback name="shot flow rate" description="" value="" unit="Kg/sec"
>shotFlowRate</Feedback>
      <Feedback name="process time" description="" value="" unit="hrs"
>processTime</Feedback>
      <ProductProcessInformation category="Process" description=""
name="percent coverage" value=""
unit="%">percentCov</ProductProcessInformation>
      <ProductProcessInformation category="Process" description=""
name="machine efficiency" value="" unit="%">E</ProductProcessInformation>
      <ProductProcessInformation category="Process" description=""
name="batchtime" value="" unit="%">batchTime</ProductProcessInformation>
      <ResourceInformation category="Shot" name="shot mass" description=""
value="" unit="Kg" >m</ResourceInformation>
      <ResourceInformation category="Shot" name="shot velocity"
description="" value="" unit="m/s" >shotVelocity</ResourceInformation>
      <ResourceInformation category="Shot" name="shot volume" description=""
value="" unit="m^3" >v</ResourceInformation>
      <ResourceInformation category="Shot" name="shot density" description=""
value="" unit="Kg/m^3" />
      <ResourceInformation category="Shot" name="shot radius" description=""
value="" unit="m" >r</ResourceInformation>
      <Transformation>
        <Equation category="Time" description="process time equal to coverage
times batch time" set="">processTime = percentCov/100*batchTime</Equation>
        <Equation category="Shot" description="mass of shot consumption"
```

```
        <Equation category="Shot" description="shot power" set="">shotPower =
(0.5*shotFlowRater*shotVelocity^2/(3600*1000))/E</Equation>
        <Equation category="Energy" description="on site <Linking>
  <LinkingAction targetUMP="Shot Peening" sourceUMP="Recovery Anneal" description="" allocationVariable="1">
      <Transformation targetInput="Process Time"  sourceOutput="Yield
Strength" description="yield strength of the tempered workpiece will influce
shot peening process time since the peening aparatus can only cover a smaller
portion of area per unit time">
        <Equation description="the equation to convert yield strength into
coverage impact area" allocationVariable="1">
              Z=100*[1-exp((-
3*beta*0.05*flowrate*pressure*nozzlelength*(sin(theta^2)))/(2.5*shotdensity*(
tan(nozzleangle)*standoff^2*yieldstrength*pi*shotradius^2)))]
        </Equation>
        <!--Equation description="determining the coverage factor K">
                >K = (feedrate*impactarea)/(shotmass*Z)
        </Equation-->
        <Equation description="find the moving coverage factor using the
transfer speed to determine how long it will take to peen the workpiece to a
predetermined coverage percentage" allocationVariable="1">
              Kaverage =
feedrate*impactarea*((2*sqrt(Z))/3.14)/(shotmass*Z*(transferspeed +
((2*sqrt(Z))/3.14)))
        </Equation>
        <Equation description="find the process time to fully peen the area Z
based on desired coverage percentage (total is 99%) and coverage factor
(Kaverage)">
              Ztime=ln(1-C/100)/-Kaverage
        </Equation>
        <Equation description="find total process time by dividing total
workpiece surface area by Ztime for a rought approximation ">
              processTime=surfacearea/Ztime
        </Equation>
        <EquationVariables description="mass flow rate" category="Shot"
set="" origin="Shot Peening">flowrate</EquationVariables>
        <EquationVariables description="shot density" category="Shot" set=""
origin="Shot Peening">shotdensity</EquationVariables>
        <EquationVariables description="pressure" category="Shot" set=""
origin="Shot Peening">pressure</EquationVariables>
        <EquationVariables description="nozzle length" category="Shot" set=""
origin="Shot Peening">nozzlelength</EquationVariables>
        <EquationVariables description="nozzle angle" category="Shot" set=""
origin="Shot Peening">nozzleangle</EquationVariables>
        <EquationVariables description="shot radius" category="Shot" set=""
origin="Shot Peening">shotradius</EquationVariables>
        <EquationVariables description="beta" category="Shot" set=""
origin="Shot Peening">beta</EquationVariables>
        <EquationVariables description="youngs modulus" category="Mechanical"
set="" origin="Tempering">youngsmodulus</EquationVariables>
        <EquationVariables description="yield strength" category="Mechanical"
set="" origin="Tempering">yieldstrength</EquationVariables>
      </Transformation>
    </LinkingAction>
       <LinkingAction targetUMP="Liquid Spray Coating" sourceUMP="Shot
Peening" description="description1" >
```

```
      <Transformation targetInput="Surface Area" sourceOutput="Impression
Depth" description="description1">
        <Equation
description="description1">impressionDepth=constant*constant*(1-
modElastic^2)^.25*shotDensity*(shotVelocity^.5/brinellHardness^.25)</Equation
>>
        <Equation
description="description2">areaIndent=2*3.14*impressionDepth^2</Equation>>
        <Equation
description="description3">totalAreaImpressions=surfaceArea/areaIndent*areaIn
dent*coveragePerc</Equation>
        <Equation
description="description3">surfaceArea=totalAreaImpressions+surfaceArea*(1-
coveragePerc)</Equation>
        <EquationVariables description="description1" category="category1"
set="set1" origin="origin1" />
        <EquationVariables description="description2" category="category2"
set="set2" origin="origin2" />
        <EquationVariables description="description3" category="category3"
set="set3" origin="origin3" />
      </Transformation>
    </LinkingAction>
  </Linking>
      <UMP name="Liquid Spray Coating" type="Surface Finishing"
description="description2">
      <Input name="Paint"></Input>
      <Input name="Compressed Air"/>
      <Output name="Overspray"/>
      <Output name="Volume of Air Consumed">volumeAirConsumed</Output>
      <Output name="Volume of Paint Consumed"/>
      <Feedback name="Process Time" description="description4" value="0.9"
unit="unit4" />
      <ProductProcessInformation name="Overspray Margin"/>
      <ProductProcessInformation name="Rated Tool Paint Flow"/>
      <ProductProcessInformation name="Power of Air Compressor"/>
      <ProductProcessInformation name="Number of Layers"/>
      <ProductProcessInformation name="Layer
Thickness">layerThickness</ProductProcessInformation>
      <ProductProcessInformation name="Surface Area"/>
      <ResourceInformation name="Paint Density"/>
      <ResourceInformation name="Air Compressor Efficiency"/>
      <Transformation>
        <Equation category="" description="description4"
set="set4">volumeAirConsumed=toolPaintFlow*processTime</Equation>
        <Equation category="category5" description="description5"
set="set5">volumePaintConsumed=layers*surfaceArea*layerThickness</Equation>
        <Equation category="category6" description="description6"
set="set6">energyCoat=volumeAirConsumed*powerAirCompressor/60</Equation>
        <Equation category="category6" description="description6"
set="set6">massPaintConsumed=volumePaintConsumed/paintDensity</Equation>
      </Transformation>
    </UMP>
</ComposedSystem>
```

APPENDIX E: UML SWIMLANE FLOWCHART OF COMPOSABILITY APPLICATION

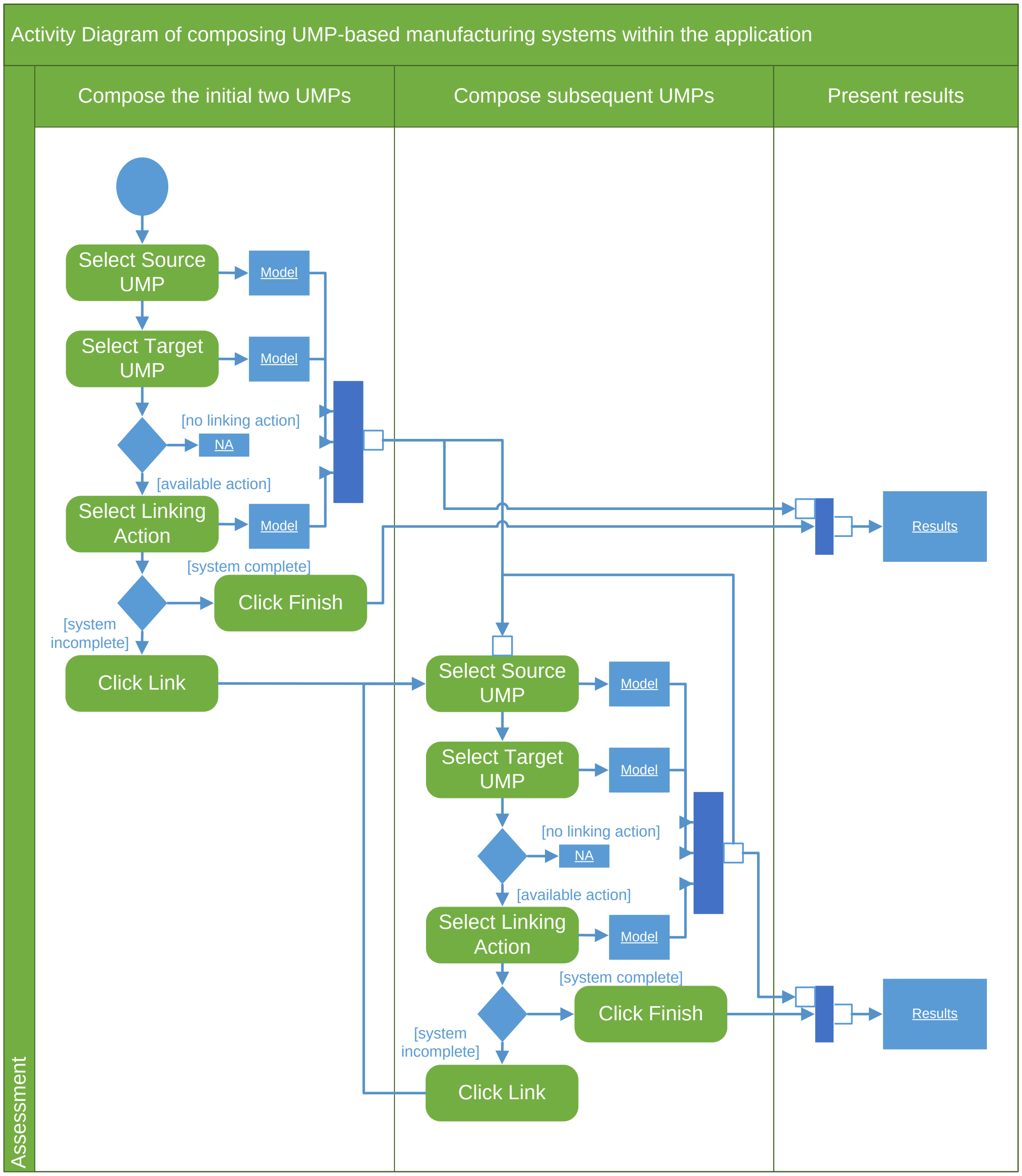


Figure 39: Activity diagram of composing UMP-based manufacturing systems for sustainable assessment within the applicati