AN ABSTRACT OF THE THESIS OF

Ian C. Garretson for the degree of Masters of Science in Industrial Engineering presented on August 28, 2015

Title: A Unit Manufacturing Process Characterization Methodology and Supporting Terminology for Sustainable Manufacturing Assessment

Abstract approved:

Karl R. Haapala

Manufacturing industry drives economic activity and growth around the world, but manufacturing activities consume large amounts of material, energy, and labor resources. Therefore, the impacts of manufacturing need to be accounted for and reduced. Direct benefits of manufacturing are products and income, which, in turn, influence the lives of people in the local community and the consumers purchasing the manufactured products. The design process for products and requisite manufacturing facilities should incorporate environmental and social criteria in addition to economic criteria to more comprehensively assess sustainability performance. Sustainability assessments for manufactured products and manufacturing facilities can be carried out by assessing the incremental elements of manufacturing industry, which are unit manufacturing processes (UMPs).

A challenge in the research area is that current methods for UMP assessment are *ad hoc* and the methods do not incorporate the system as a whole. The purpose of this research is to enable sustainable manufacturing decision making by 1) unifying an assessment methodology for UMPs, 2) developing an information modeling framework for characterizing UMPs and workpieces, and 3) demonstrating UMP composability (connectivity) modeling for use in sustainability assessments. The methodology is developed through literature review, and unifies 23 different UMP manufacturing

assessment methods by analyzing each for overlapping and unique steps in the approaches. Thus, a nine-step assessment methodology emerged, which has multiple applications in industry, including process and facility assessment and improvement.

A next step for MPF modeling is to link UMP models by modeling the workpiece state, but supporting tools were need to identifying how to correctly model the interactions between the UMP and the workpiece. The information modeling framework developed herein provides the theoretical background for how UMP models interact by linking the function of the UMP to the effect on the workpiece and by identifying the calculation variables necessary to assess UMPs. The information modeling framework developed for composing UMP models is demonstrated through the energy analysis of a metal component. The component is manufactured by recrystallization annealing, reducing (milling), through hardening, and recovery annealing (tempering). Models are composed (connected) by utilizing knowledge of how UMPs impart transformation to the workpiece and the information embedded in the workpiece that is transported to subsequent UMPs. Workpiece information includes the geometry and properties of the current state and future states. Previous work reported in literature has focused on geometry modeling (e.g. CAD, CAM), while this work focuses on property modeling. This research develops an overarching detailed approach to manufacturing sustainability assessments through in-depth analysis of UMPs. The result of using this UMP approach will provide guidance toward a more sustainable future.

A Unit Manufacturing Process Characterization Methodology and Supporting Terminology for Sustainable Manufacturing Assessment

by
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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.

Ian C. Garretson, Author

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CONTRIBUTION OF AUTHORS

Chapter 2: Manuscript 1

Ian Garretson performed a literature review to identify terminology, definitions, and synonyms from sustainable manufacturing assessment literature. Mahesh Mani, Swee Leong, Kevin Lyons, and Karl Haapala provided input and direction of the work and helpful review and feedback.

Chapter 3: Manuscript 2

Ian Garretson performed a literature review to identify methods for assessing UMPs, and created a UMP assessment methodology unifying the reviewed methods. Michael Eastwood and Christopher Eastwood were collaborators in developing the Sustainable Manufacturing Assessment Tool (SMAT), the assessment carried out in Chapter 3 utilized said tool. Matthew Carter and Ann Simmons provided feedback and helped with data collection for the SMAT tool. Mahesh Mani, Swee Leong, Kevin Lyons, and Karl Haapala provided input and direction of the work and helpful review and feedback.

Chapter 4: Manuscript 3

Ian Garreteson developed the information modeling framework presented in the chapter, and developed the example, energy models, and MATLAB code for the example. Mahesh Mani, Swee Leong, Kevin Lyons, and Karl Haapala provided input and direction of the work and helpful review and feedback.

Appendix C: Manuscript 4

Ian Garretson modeled the two inspection UMPs described in the chapter. Matthew Carter and Ann Simmons provided feedback and helped with data collection for the SMAT tool. Mahesh Mani, Swee Leong, Kevin Lyons, and Karl Haapala provided input and direction of the work and helpful review and feedback.

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NOMENCLATURE

$\%_B$	percent banite phase of the steel
$\%_F$	percent ferrite phase of the steel
$\%_M$	percent martensite phase of the steel
$\%_P$	percent pearlite phase of the steel
As	shear area of the cut
AWG	average wage
B	magnetic flux density
C_{con}	material cost
C_E	energy cost
C_i	cost of input or output i
C_{op}	operating cost
$Cost_{consumables}$	unit cost of consumables used
$Cost_{energy}$	unit cost of energy
$Cost_{labor}$	unit cost of labor
$Cost_{waste\ disposal}$	unit cost of waste disposal
$Cost_{waste\ water}$	unit cost of waste water
$Cost_{Water}$	unit cost of water
cp_i	heat capacity of i
$Days\_Lost_i$	days lost from illness i
$Days\_Lost_j$	days lost from injury j
D_{eff}	effective diameter
dFc	derivative of the cutting force
dFt	derivative of the thrusting force
dFx	derivative of the milling force in the x direction
dFy	derivative of the milling force in the y direction
D_{in}	inner diameter
DL_i	days lost by injury i
DL_j	days lost by illness j
D_{out}	outer diameter
E_{heat}	theoretical heat energy requirement
E_i	energy consumed by i
EM_{ghg}	greenhouse gas emissions
$Emissions_{direct\_combustion}$	emission as a result of combustion at the process
$Emissions_{direct\_vaporization}$	emission as a result of vaporization at the process
$Energy_{consumed}$	total energy consumed on the process
$Energy_{Cut}$	theoretical energy required for cutting
$Energy_{Mill}$	energy required for the milling machine
$Energy_{part\_caryoff}$	energy carried off by the part from the oven
$Energy_{total\_required\_oven}$	total theoretical energy required of the oven

E_T	energy consumed
$Feed_{perSecond}$	feed of milling tool per second
GWP_{CH4}	methane global warming potential
GWP_{CH4}	conversion of methane to carbon dioxide derived from radiative forcing
GWP_{N2O}	nitrous oxide global warming potential
GWP_{N2O}	conversion of nitrous oxide to carbon dioxide derived from radiative forcing
$Heat_{Convection}$	heat lost to convection of the oven
$Heat_{flue\_gas\_loss}$	heat lost from the flue gas of the oven
$Heat_{oven\_wall\_loss}$	heat lost from the wall of the oven
$Heat_{Radiation}$	heat lost to radiation of the oven
Hv	Vickers hardness of the component in kgf/mm^2
Hv_B	Vickers hardness of the banite phase
Hv_{FP}	Vickers hardness of the ferrite and pearlite phase
Hv_M	Vickers hardness of the martensite phase
ILL_j	number of unique illness j
$Illness\_i_{Number\_of}$	number of unique illness i
INJ_i	number of unique injury i
$Injury\_j_{Number\_of}$	number of unique injury j
IR	irradiance
I_{wire}	current through a wire
k	heat transfer coefficient
K_i	empirical constant relating current to component and loop geometry
L_i	length or thickness of i
$Mass_{consumables}$	mass of consumables used
$Material_{processed}$	amount of material processed
M_{con}	material consumed
M_i	mass of object or consumable i
$M_{pro,i}$	material processed machine i
MRR	material removal rate
N_{loop}	number wraps of the loop
$N_{revolutions}$	number of revolutions for the milling process
Nt	number ot cutting teeth on milling tool
Percent_Cut_Energy	percent energy of total used for cutting on a milling machine
$Percent_{non-water}$	percentage of non-water of a fluid
$Percent_{water}$	percentage of water in a fluid
P_i	machine i power
$P_{ILL,i}$	probability of illness i occurring
$P_{INJ,j}$	probability of injury j occurring

$\text{Power}_{\text{empirical}}$	machine power as an empirical function
$\text{Power}_{\text{process\_parameters}}$	machine power as a function of process parameters
$\text{Power}_{\text{workpiece\_geometry}}$	machine power as a function of workpiece geometry
$\text{Probability\_}_{\text{Days\_Lost\_l}}$	days lost from illness of injury k
$\text{Probability}_{\text{Illness\_injury\_k}}$	probability of illness or injury k
q_i	heat of i
r	distance vector between the component and the wire
$\hat{r}$	unit vector of r
R_{air}	air flow of oven
Rate_{CH4}	conversion rate of methane from electricity generation
Rate_{CO2}	conversion rate of carbon dioxide from electricity generation
$\text{Rate}_{\text{comsumable\_per\_part}}$	consumable use rate per material processed
$\text{Rate}_{\text{dragout}}$	dragout rate of a fluid
$\text{Rate}_{\text{material process}}$	material processing rate
Rate_{N2O}	conversion rate of nitrous oxide from electricity generation
$\text{Rate}_{\text{waste}}$	rate of waste production
$\text{Rate}_{\text{water\_use}}$	water use rate
R_{CH4}	methane production rate
R_{CO2}	carbon dioxide production rate
R_{H2O}	flow rate of water
$R_{haz,I}$	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_{Loop}	radius of magnetizing loop
R_{N2O}	nitrous oxide production rate
$R_{rec,I}$	waste to recycling production rate of machine i
$R_{wat,I}$	water use rate machine i
R_{wire}	radius of wire
R_{Ω}	resistance of a wire
$\text{t\_}_{\text{reduce}}$	time required for the reducing process
t_{BTR_i}	time between replacement of i
Temp_IC	intercritical temperature required of component to be tempered
$\text{Thickness}_{\text{Component}}$	thickness of the component or part
t_i	process time task i
T_i	temperature of i

$Time_{Austenization}$	time required for a steel component to fully austenize
$Time_{BTRF}$	time between replacement of a fluid
$Time_{Laborer\_k}$	time spent working of laborer k
$Time_{perThickness}$	time required as a function of part thickness to austenize
$Time_{process}$	process time
$time_{Revolution}$	time for milling tool to complete one revolution
t_L	labor time
$t_{L,i}$	time worked of laborer i
t_p	process time
$UseRate_{consumables}$	rate of consumption of consumables
V_{H2O}	water use
VMR	volume of material removed
$Volume_{tank}$	volume of a tank
$Wage_{Laborer\_k}$	wage rate of laborer k
$Waste_{total}$	total waste generated on the process
$Water_{consumed}$	total water consumed on the process
W_i	wage of laborer i
WST_T	total waste produced
Y	fill factor
α	solid angle
α	rake angle
β	friction angle
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

CHAPTER 1: INTRODUCTION

1.1 Motivation

Manufacturing science and industrial production technology advances in response to growing human needs for higher-quality, more-complex products. Manufacturing technologies in turn are the resources for creating objects that make life easier and more enjoyable. By advancing manufacturing technology a society benefits economically by creating unique exportable products, socially by generating value adding jobs, and environmentally by increasing manufacturing efficiency. While many benefits are had, often unwanted consequences result from industrial production. Positive and negative consequences of human development and subsequently manufacturing can be measured within the guidelines of the three aspects of sustainability: economic, environmental, and social. Authors have expanded on these aspects, e.g., Jovane et al. [1] includes technology and United Cities and Local Governments (UNLG) [2] includes culture as aspects, but economic, environmental, and social are adequate for capturing the impacts of unit manufacturing processes.

Sustainable development was defined in the Brundtland Report [3] as, “development which meets the needs of the present without compromising the ability of future generation to meet their own needs.” This definition was adapted by Mihelcic et al. [4] to define sustainable engineering as, “the design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment.” Both definitions provide foreseeable goals for manufacturing, as being an enabler of sustained life quality for future generations. US water and energy consumption is expected to increase between

Energy consumption in the United States is projected to grow in the industrial sector from $32.1*10^9$ GJ to $40.4*10^9$ GJ from 2011 to 2040 [5], or 26% growth in 29 years (annual growth of 0.9%); and Gutowski et al. [6] reported global per capita manufacturing power consumption was 467 watts/person in 2010 and was growing at a rate of 1.6% annually. They also reported global per capita emissions of carbon dioxide from industrial activities were 0.9 tons/person/year in 2010 and growing at a rate of 2.5% annually – a significantly higher annual rate than power demand growth. There is a need to curb this growth in power consumption and emissions. In addition, US water consumption is projected to grow from 432 GL to 514 GL per day from 2005 to 2030 [7], a 19% growth over 25 years (annual growth of 0.8%). US GDP is expected to grow 2.4% annually between 2012 and 2040 [5], and US manufacturing employment is expected to decrease between 2012 and 2022 by 0.5% annually; conversely, total employment in the U.S. is expected to increase by 1% annually [8]. Sustainable economic growth patterns are needed for continued quality of life for future generations, and consumption growth needs to be reversed to reduce impacts of resource use.

Sustainable production of industrial products can be approached using a multitude of methods, which are rooted in proactive and non-proactive philosophies. Environmental problems can be solved proactively, leading to reduced process by-products and wastes, and improved efficiency. Alternatively, non-proactive solutions, or end-of-pipe solutions, generally result in more systemic by-products that require either additional processing or finding additional uses to eliminate the resulting waste. Social consequences of manufacturing can be perceived as resulting from decisions made either at the enterprise level or the individual level; thus determining responsibility of consequential worker problems yield different. Finally, economic impacts are again a reflection on different philosophies, widespread benefit or personal gain. American corporate culture is rooted in rugged individualism, but that culture does not always lead to equal benefits for the people that run and society that supports American companies.

Similar to The Belmont Report’s [9] exposé on justice, equal benefits should be derived from the manufacture of products and the impact of manufacturing products. The

Belmont Report questions the justice of the distribution of research, “Who ought to receive the benefits of research and bear its burdens?” Similarly, justice is needed in manufacturing; a Marxist distribution of profit is not required, but the distribution of the impact and ramifications of manufacturing should be equal to the distribution of benefit. The result of manufacturing, a product, is often perceived as having a beneficial impact on society, whereas the act of manufacturing and its societal impact are less apparent. This is because manufacturing serves as a means to create useable products, which, in turn, serve to achieve some Maslowian need. Whereas, a process adds incremental value to a product, but does not provide philological, safety, belonging, esteem, or self-actualization to a person. Within the confines of an industrial facility, however, products can be assessed by analyzing, interpreting, and aggregating the fundamental quantifiable impact of unit manufacturing processes (UMP), as described below.

1.2 Background

Little [10] was identified by Shreve [11] as providing the first formal definition of a *unit operation* (and *unit process*) in 1925. Little stated, “[P]rocesses for the conversion of raw materials into products of higher value, and practically all such processes can be resolved into a sequence of *unit operations*” [10]. Groggins [12] was identified by Shreve [11] as the first to recognize a distinction between a *unit operation* and *unit process*, in 1935, where the former is for mechanical transformations and the latter is for chemical transformations. This distinction is useful for the chemical industry, but the distinction is not useful in manufacturing, as noted by Todd et al. [13], [14], and the two terms are used synonymously in this research. The National Research Council (NRC) [15] formalized the definition of a unit manufacturing process (UMP) as, “the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product.” This definition will be used throughout this work to describe a unit operation, unit process, or, synonymously, a UMP.

As the definition of a UMP has become formalized, the conceptual representation of a UMP has been formalized as well, as seen in Figure 1.1. In manufacturing, the first UMP model was developed by Kim et al. [16] who represented a UMP using IDEF0. Representations of UMP models have been subsequently refined and altered, and Table 1.1 documents prior research that has defined UMP conceptual models. The ASTM WK35705 [17] work group is developing a standard for Sustainability Characterization of Manufacturing Processes and has defined a UMP model that is a modification of the NRC representation. The WK35705 modified UMP model captures more detail of UMP resources, that was not represented in the original.

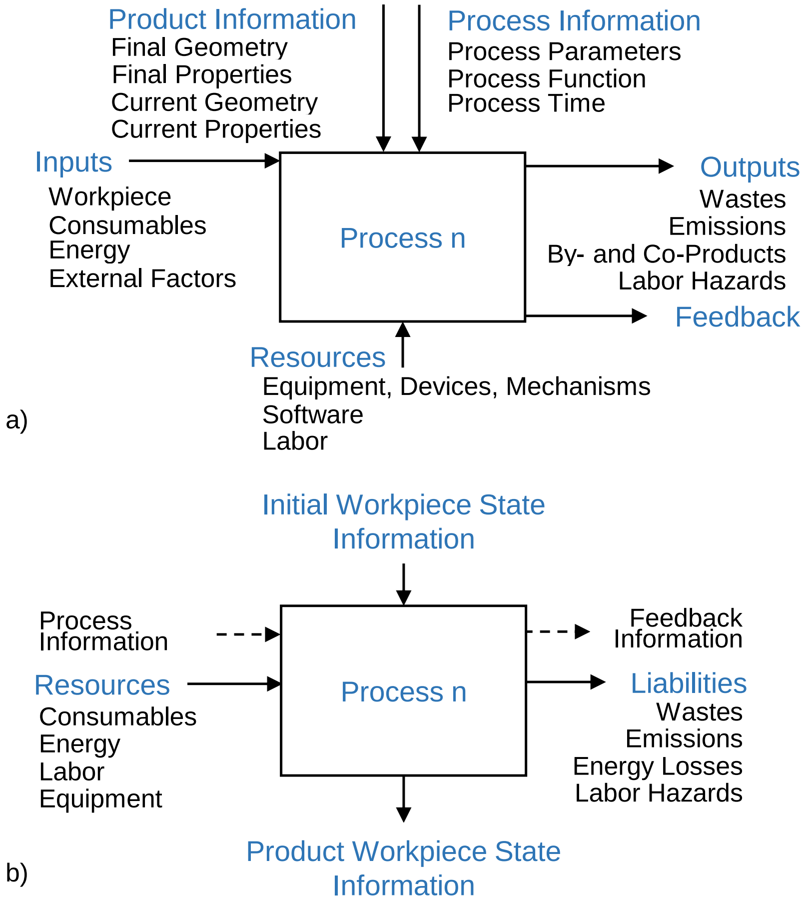

Figure 1.1 Conceptual representations of a unit manufacturing process. a) emphasis on information categories (adapted from [17]) and b) emphasis on workpiece flow (adapted from [17]).

Unit manufacturing processes are categorized using UMP taxonomies [13], [18], [19]. The three most widely applied were reported by Todd et al. [13], Groover [19], and the German Institute of Standardization [18]. These taxonomies have similar overarching categories, but each uniquely categorizes UMPs [20]. The taxonomy defined by Todd et al. [13] is examined herein. UMPs are organized into two overarching areas: 1) shaping, which defines processes that change the geometry or shape of a workpiece, and 2) non-shaping, which defines processes that change the properties of the workpiece. A few processes can be classified as both shaping and non-shaping (e.g., shot peening) but when designated in a manufacturing process flow (MPF) the selected UMP usually has a primary objective (e.g., achieve dimensional tolerances or remove residual stresses); and, inconsequentially, both geometry and property changes occur to the workpiece. Todd et al. [13] further classified the transformation or function of the UMPs into mechanical, thermal, or chemical processing energies. Finally, they defined the state of the workpiece material within the UMPs as either solid, granular, liquid, plastic, preparation, or coating. These aspects are summarized in Table 1.1, below.

Table 1.1: Taxonomy for Unit manufacturing processes; 1-6 geometry change Processes, 7-10 property change Processes (Adapted from Todd et. al. [13])

	Type of Process	State of Material	UMP Transformation
1	Mass-reducing	Solid	Mechanical
2	Mass-reducing	Solid	Thermal
3	Mass-reducing	Solid	Chemical
4	Mass-conserving	Solid/granular	Mechanical
5	Consolidation	Liquid/plastic	Mechanical
6	Joining	Solid (except adjacent surfaces)	Mechanical
7	Hardening	Solid	Chemical/thermal
8	Softening	Solid	Chemical/thermal
9	Surface treatment	Preparation	Mechanical/thermal/chemical
10	Surface treatment	Coating	Mechanical/thermal/chemical

The definition, representation, and categorization of UMPs are used throughout this work, and are necessary for characterizing UMPs for interchangeability and customizability within MPFs for sustainable manufacturing assessment. A variety of definitions, representations, and categorizations have been reported in the research literature for individual UMPs, thus standard UMP characterization is needed. In particular, prior work has used a multiplicity of terminology to describe various processes often with duplication or without formalizing definition of terms. In addition, previously reported UMP modeling and characterization approaches are conducted in an *ad hoc* nature, which results in collection of information with a non-standard fashion (e.g., the various UMP models require different types and forms of data and information). Finally, as there have been various methods for collecting UMP related information, this results in various modeling structures which limits aggregate use of UMP models for manufacturing system sustainability assessments.

1.3 Research Objectives

The primary objectives of this thesis research are to define the terminology, create a UMP assessment methodology, and create an information modeling framework for characterization of UMPs and composability of UMP models. This terminology, methodology, and framework will enable detailed and comprehensive sustainability assessments of products, discrete manufacturing processes, and manufacturing facilities. From this objective the following questions are derived:

Question 1: What activities are required to conduct sustainability assessment of unit manufacturing processes?

Question 2: What data and information has to be measured, collected, or generated to determine the sustainability performance of a unit manufacturing process?

Question 3: How is information transferred between unit manufacturing processes and how can this information transfer be captured to compose mathematical models of unit manufacturing processes into a process flow?

1.4 Research Tasks

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

Task 1: to develop a methodology for sustainability assessment of UMPs. Subtasks include surveying the literature to identify existing sustainability assessment methods, identifying commonalities and differences between the existing methods, and creating a unifying methodology.

Task 2: to identify the information required to assess UMPs from a sustainability perspective. Subtasks include identifying different UMP types, identifying the unique and common parameters for the various UMP types, identifying the mathematical relationships to describe sustainability performance metrics for each UMP, and creating generalized mathematical models to describe various UMPs.

Task 3: to create an information modeling framework to capture information transformations between subsequent UMPs within an MPF, which will ultimately enable the composition of UMP models. Subtasks include understanding how information is transferred between subsequent UMPs within an MPF, creating an information modeling framework, and conceptual demonstration of the framework.

1.5 Thesis Outline

This research conducted as a part of this thesis is reported in manuscript format and includes 5 chapters and several Appendices, all of which are used for sustainability analysis of manufacturing systems. A system is defined as, “a perceived whole whose elements are ‘interconnected’ and have a purpose in a given context”[1]. The purpose of the system studied in this thesis is to convert input raw materials to a final product. The system context is aircraft metal product manufacturing system, wherein devices and mechanisms are used to modify metal components to adding value and transforming them into products. The product manufacturing system is made up of UMPs (devices and mechanisms) and MPFs (multiple UMPs) within a facility (multiple MPFs), or set of facilities. These systems and subsystems are analyzed and communicated using the work described herein, which includes terminology to describe sustainable manufacturing assessments, a methodology for assessing UMPs, and an information modeling framework for organizing the data within a UMP model. In sum, the work provides a means for performing product sustainability assessments, based on the UMPs, MPFs, and their underlying interrelations and structure.

Chapter 1 provides an introduction to the research including motivation, objective, and tasks.

Chapter 2 presents a review of the literature (submitted to the *Journal of Cleaner Production*). It describes the background of UMP characterization and assessment, as well as identifying and defining the common terminology used within the research domain.

Chapter 3 is an article to be submitted to the *Journal Manufacturing Science and Engineering*, and captures a multitude of methods used to assess UMPs. It also presents a unifying methodology developed in this research to assess the sustainability performance of UMPs and products. The methodology is demonstrated on an aircraft-like assembly.

Chapter 4 is an article to be submitted to *Advanced Engineering Informatics*, and creates an information modeling framework to capture UMP information and workpiece information. It also conceptually demonstrates the framework for characterizing energy consumption for the MPF of an aircraft-like component.

Chapter 5 summarizes the research performed, presents the research findings, conclusions, and contributions, and identifies opportunities for future work.

Appendix A presents generalized IDEF0 models conceptualizing UMP mathematical modeling for Chapter 4. The conceptual models were unified from a collection of discrete UMP models to capture all relevant informational considerations of UMP modeling.

Appendix B is a mathematical model written in Mathworks© MATLAB language used for exceuting the mathematical models developed in the Chapter 4 exmple.

Finally, Appendix C is a conference article published in the *Proceedings of the ASME 2015 International Design Engineering Technical Conferences*, and presents UMP models for characterizing magnetic particle inspection and penetrant testing processes. This is the first known work to investigate inspection processes from a sustainability perspective. Inspection processes use relatively little energy and material resources, but represent a process bottleneck in aerospace manufacturing and require a significant amount of time and skilled labor resources.

CHAPTER TWO: MANUFACTURING PROCESS CHARACTERIZATION TERMINOLOGY TO SUPPORT SUSTAINABILITY ASSESSMENT

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CHAPTER 2: MANUFACTURING PROCESS CHARACTERIZATION TERMINOLOGY TO SUPPORT SUSTAINABILITY ASSESSMENT

2.1 Abstract

Common terminology is essential for accurate communication between researchers, scientists, engineers, and other decision makers. For manufacturing process characterization, identifying a common understanding of terminology is imperative for efficient communication in the manufacturing industry and to facilitate automation and interoperability of software tools. Manufacturing process characterization is a method that enables the assessment and improvement of unit processes, products, and manufacturing systems.

Characterizing manufacturing processes provides a means to account for the impact of individual manufacturing processes, with applications in sustainability assessment. The development of sustainability-related standards internationally is evidence that the field is quickly maturing. To develop and transfer sustainability-related standards and best practices to the industry, naming conventions and definitions of common terms are needed. Presently, many terms used in practice are ill-defined, vague, or overlap in meaning. Although there are ongoing standards efforts related to terminology identification and definition, an identified common set is yet to be developed.

The objective of this work is to facilitate such ongoing efforts by harmonizing a varying array of terms used to broadly describe manufacturing processes into a concise set, terminology omitted are those unique to individual manufacturing processes. Thus, a list of common terms focusing on process characterization and able to describe sustainable manufacturing is reported. Definitions of these common terms are then derived from a literature review of sustainable manufacturing and chemistry, process characterization and planning, organization standards, and life cycle assessment and management. It can

be noted that the terminology reviewed for unit manufacturing process characterization are not unique to the domain of sustainable manufacturing. It is hoped that the reported terms and definitions will facilitate sustainability-related standards development and enable widespread use of the concepts for manufacturing process characterization, for improving the economic, environmental, and social performance of businesses.

2.2 Keywords

Process characterization, terminology, sustainable manufacturing, process modeling, unit process, manufacturing

2.3 Introduction

Manufacturing is a main focus of sustainability-related research, reports, and legislation because it is commonly the source of many environmental hazards and ecological implications. Early legislation in the U.S. began to appear in the late 1940s with the Water Pollution Control Act (1948). In the 1960s the Clean Air Act (1963) was followed by National Environmental Policy Act (1969), which was legislation for the enforcement of sustainability policies. Soon after, in 1970, Environmental Protection Agency (EPA) in 1970 [21] came into being.

Two other industrial nations enacted similar laws around the same time: Japan’s Pollution Diet (1970) and West Germany’s Federal Environmental Agency (1971) [21]. International efforts soon arose as meetings and subsequent reports, e.g., UN Conference on Human Environment (1972), the Brundtland report (1987), Earth Summit in Rio (1992), and Agenda 21 (1992). The Brundtland report (1987) was especially significant since it proposed a definition for sustainable development as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs.”

Elkington [22] posited that businesses must include natural and social capital, not just economic capital, in their management plans to achieve a positive triple bottom line (people, profit, and planet). Thus, the definition has been expanded to include the triple bottom line, and has also been adapted by Dyllick and Hockerts [23] to address corporate sustainability: “meeting the needs of a firm’s direct and indirect stakeholders (such as shareholders, employees, clients, pressure groups, and communities), without compromising its ability to meet the needs of future stakeholders as well.”

The new century saw a change for sustainability as a noun to sustainable as an adjective. Sustainable design, as an engineering function within industry, was addressed by Mihelcic et al. [4] as “the design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment.” Sustainable manufacturing was defined decade later by the U.S. Department of Commerce (DOC) [24] as “creation of a manufactured product with processes that have minimal negative impact on the environment, conserve energy and natural resources, are safe for employees and communities, and are economically sound.” These two definitions reflect the ideas originally presented in the Brundtland report and by Elkington’s triple bottom line. Both definitions assert that there are negative environmental, economic, and social impacts related to the manufacturing industry that must be reduced to sustain and support the development of global civilization.

Many companies have developed sustainability metrics and indicators as a first step toward reducing such negative impacts, that quantify the economic, environmental, and social performance of business practices [25]. To quantify sustainability performance, life cycle assessment (LCA) methods, which have been implemented in numerous software tools, are commonly used. These methods are often opaque, costly, and time consuming; and, existing tools provide can provide performance assessments, but little guidance for performance improvement. Reap et al. [26], [27] reported that many problems arise due to information about and use of the functional unit (Section 2.6.6.1), and system boundary definitions, allocation and flow analysis, and the subjectivity introduced by aggregation of impact data.

To address these problems, more comprehensive, sustainable, product-design methods have been developed [28], [29], but these often omit detailed evaluation of manufacturing system performance. Unit manufacturing process (UMP) characterization can be used to perform detailed manufacturing system assessments, and thus fill this gap. UMPs were first identified by the National Research Council (NRC) [15] as an area for engineering research, and the generalized unit manufacturing process characterization method was subsequently developed using specific case studies, e.g., [30]–[32], and further developed more recently into fully defined methods, e.g., [33]–[36]. Unique case studies are still being published, e.g., [37], to support methodological development efforts.

In today's competitive global market, manufacturers are being compelled to create and deliver high quality products in a cost effective and socially responsible manner, while reducing the environmental impacts of their activities [15]. Thus, a key challenge lies in effectively quantifying and communicating sustainability performance of manufacturing processes to facilitate decisions to improve that performance. Current industry practices to compute sustainability performance are not standardized. Consequently, these practices rely on *ad hoc* information and non-uniform methods to calculate the performance of manufacturing processes and equipment. There is growing interest from industry, government agencies, and standards development organizations to change this situation by developing sustainability-related standard guides to facilitate such communication and decision making.

One such effort is being pursued by the American Society for Testing and Materials (ASTM) International [17]. The scope of the ASTM sustainable manufacturing standards (currently in the form of work items) addresses the evaluation aspects, terminology, characterization of manufacturing processes, and classification of waste at manufacturing facilities.

The guides currently being developed are envisioned to assist manufacturers in characterizing manufacturing processes for sustainability and to support relevant decision making. To transfer sustainability-related standards and guides to the industry, however, requires a common language (terminology and definitions). Presently, many terms used in the area of sustainable manufacturing are ill-defined, vague, or overlap in meaning. Although there are ongoing terminology-related standards efforts including ASTM, an identified a common set of terms and definitions is yet to be developed. This paper proposes a set. Specifically, the objective is to identify a standardized language for unit manufacturing process characterization, which can then be used to support sustainability assessment of manufactured products, manufacturing processes, and manufacturing systems. A detailed UMP characterization can be used within bottom-up analysis approaches to conduct product sustainability assessments. Because an overarching aim is to enable broadly usable sustainable manufacturing assessments, the terminology is identified primarily from sustainable-manufacturing and life-cycle-assessment literature. The literature was selected to ensure definitions appropriate to the contextual domain under study. Many of the terms have commonly accepted definitions, which are included here for completeness. While we recognize the need for supporting ontologies and methods for UMP characterization, that need is beyond the scope of this paper.

2.4 Method for Terminology Definition

Seuring and Müller [38] reported that literature reviews accomplish two objectives: “first, they summarize existing research by identifying patterns, themes and issues. Second, this helps to identify the conceptual content of the field and can contribute to theory development.” From this viewpoint, the goals of the literature review herein are 1) to summarize the language and concepts used in manufacturing process characterization for sustainability assessment and 2) to enable the development of supporting theory, methods, and industrially relevant tools. Themes from the field will arise as a consequence of this goal. Beruvides and Omachonu [39] described a ten-step process that is adapted to assist in the literature review. The first three steps (Steps 1-3) of their process direct the early stages of the literature search. The next four steps (Steps 4-7) describe article organization. The eighth step (Step 8) analyzes the data and content using several methods. The next two steps (Steps 9-10) address the identified gaps, reporting, and actions. The steps undertaken in the literature review presented here uses a similar approach as follows:

1. Review literature to identify relevant areas for terminology search
2. Generate initial set of key terms and corresponding references
3. Identify explicit definitions that are self-contained and clear
4. Generate a matrix of terms and definitions to categorize the terminology
5. Review the matrix to identify gaps and overlaps
6. Check and harmonize the terminology

Since the purpose of the review is to identify, define, and harmonize terminology, rather than identifying broader themes and directions, the steps specified in prior work for article organization are not necessary. Relevant sources for definitions were identified from several research areas including life-cycle assessment and management, manufacturing process modeling, sustainable chemistry, sustainable policy, organizational standards, and process planning. Definitions that were explicitly stated were used from references – note that references that made use of a term but did not define it explicitly were not used. An evolutionary method was used to select and organize the relevant terminology from the body of research. Relevant categories were identified from the aspects of UMP characterization, sustainability assessments, and the general patterns of the terminology. Terms that did not fit into a relevant category were initially excluded from the list, but were added later - as new terms or synonyms - as the review and harmonization proceeded.

The initially defined categories were boundary, data, decision, measurement, policy, process, and general. From these categories, the data category was combined with the measurement category since few relevant data terms were identified in the review. The policy category was combined with the general category, since the focus of the work is on modeling and assessments, and not company or government policy. To better define several higher-level concepts, the categories of flow, scope, and taxonomy were added as the review proceeded. Thus, the second set of categories included boundary, flow, material, measurement, model, process, scope, and taxonomy. As the review proceeded, the process and taxonomy categories were found to be redundant, in that the terms included could be better attributed to the flow, model, and scope categories. The final set of categories defined became boundary, flow, material, measurement, model, and scope. While others could be defined, this categorization approach was found to be useful in organizing the terminology identified.

In deciding whether to include a term in the categorization for further research and definition harmonization, the primary criterion was its relevance in answering the question, “How is a unit manufacturing process described?” As the categorization of terms proceeded, some terms emerged as synonyms for other identified terms. These synonyms aided in further defining the meaning of each particular term. Based on the references used to identify key terms and synonyms, definitions were generated and harmonized for each identified key term. In many cases, previously established definitions were found to be suitable and were not modified further.

2.5 Literature Review

Embracing sustainability has been an active task arguably since the Brundtland Commission presented its definition of sustainable development, and, prior to that, as less connected elements of environmental and social development initiatives. Society has begun addressing and incorporating sustainable development into research and common practice through the use of indicators [40]. More broadly, sustainability has been incorporated into the development of a wide array of technologies and systems including sustainable energy generation [41], sustainable mineral processing [42], sustainable construction [43], and sustainable supply chains [38]. Many reviews have been completed from different viewpoints including sustainable manufacturing perspectives, corporate perspectives and challenges [44], [45], global manufacturing challenges [1], [6], discrete product/process/system challenges [46], and LCA integration into manufacturing decision making [47]. Literature reviews have been completed for sustainable chemical industry perspectives [48], [49]. Reviews also have been completed for manufacturing process modeling, e.g., general approaches, [20], [50], machining [51]–[53], metal forming [54], and dry processing [55].

While the domains of these reviews overlap, they do not completely capture the terminology of sustainable manufacturing process modeling. The following sections outline previous review articles related to sustainable manufacturing process modeling, and move from broad concepts to specific applications. The sections present terminology-related work aligned with sustainable practices in the manufacturing and chemical industry, followed by a process characterization point of view. Based on the review, key terms and corresponding papers used in defining the terms are summarized. A common theme of prior studies shows that increasing global competition is driving the need for more sustainable practices.

2.5.1 Sustainability Practices in Manufacturing

Notably, an article by Glavic and Lukman [56] developed definitions of terms for policy and decision making related to sustainable manufacturing. Press [57] stated that policy will cause incremental improvements, but will not cause acceptance of best available technologies (BATs). Both papers posited the same conclusion: voluntary action taken by firms and wide information dissemination relating to technology use enables the greatest improvement. Press pointed out that research is needed to determine the effects that policies have on manufacturing improvements. Hahn and Kühnen [58] evaluated the determinants of sustainability reporting in business and academia; they concluded that corporation size, visibility, and sector-affiliation were the most significant. Furthermore, Hahn and Kuhnen identified research gaps, which included a need for 1) investigating the impact of report quality on stakeholder perception and understanding and 2) understanding the influence of regulation and governance on reporting. Kunz et al. [59] investigated natural sciences, engineering, and management literature to find the intersection of human and engineered systems, termed coupling for sustainability, from both the technical and social perspectives. Kunz et al. argued that industrial sustainability has traditionally addressed technical systems, for example energy efficiency. They suggested that incorporation of strong human coupling into research and industrial practice is needed. Research areas include identifying and measuring strong coupling and determining ways to move from weak to strong coupling.

Implementation of sustainability policy in manufacturing has largely been evaluated with life cycle analysis (LCA) to assess environmental impacts [60]. Westkamper et al. [47] analyzed the assessment and management of products from a life-cycle perspective and reviewed the intelligent manufacturing system (IMS) concept. They concluded that industry should use LCA to assimilate broad implications into corporate decision making, to enable organizations to provide more sustainable products, and to encourage more widespread use in developing countries. Finnveden et al. [61] reviewed LCA practices and found that aspects of the method had significantly matured with the development of databases, quality assurance, consistency, and harmonization. However, they found more improvements were needed, including aspects of goal and scope definition, resolving differences between attributional and consequential LCAs, developing methods for more accurate impact assessments on ecosystem services, and for prioritization of database development. Pryshlakivsky and Searcy [62] investigated the development and improvement areas of the ISO14040 LCA standards developed by the International Organization for Standardization (ISO). They noted that, while LCA has grown rapidly, a systematic, non-expert tool is required for incorporating the analyses into more fields of study. They also concluded that evaluation of the functional effectiveness of the standards is needed.

Several reviews have focused on sustainable manufacturing practices. Jovane et al. [1] asserted that competitive sustainable manufacturing (CSM) must be implemented globally for manufacturing and services industries to address growing economic, social, environmental, and technological (ESET) challenges. They posited that CSM is needed for continued growth without depleting ESET resources. Arena et al. [44] addressed sustainability from an operational point of view through an in-depth analysis of 1) sustainability definitions within different performance areas, 2) sustainability tools within different performance areas, 3) quantitative and non-quantitative measurement methods, and 4) indicator completeness. Hossain et al. [63] reviewed existing pollution-prevention frameworks in both the design and retrofit stages. Using LCA, they developed an evaluation framework to determine the best pollution-prevention designs and technologies. Ilgin and Gupta [64] analyzed progress made in environmentally conscious manufacturing and product recovery (ECMPRO) since Gungor and Gupta’s similar work [65]. Suggested research areas include product life cycle, disassembly, material recovery, remanufacturing, and, pollution prevention. Among other needs, the authors identified a need for environmentally conscious design methodologies that integrate design of products and processes, a need for strategic models that go beyond operations and tactics of firms to analyze the technological and organizational dynamics of ECMPRO systems, and, finally, a need to incorporate these into engineering curricula.

Similarly, Haapala et al. [46] investigated engineering-research needed to support sustainable manufacturing, including the influence of metrics on design and manufacturing decision making, research opportunities for various manufacturing processes, and manufacturing-system and supply-chain-planning issues. Gutowski et al. [6] analyzed the global carbon emissions caused by manufacturing and then further investigated the five major materials contributing to energy consumption and carbon emission: 1) iron and steel, 2) cement, 3) plastics, 4) paper, and 5) aluminum. Most recently, Bolis et al. [66] claimed that the term sustainable development has taken on too many meanings and needs to be redefined. They developed a Sustainable Development with an Axiological Perspective (SD-AP) model to guide the discussion for redefining sustainable development. The model incorporated the triple bottom line, generational needs, and value-based decision making, thus creating an integrated perspective. Ibáñez-Forés et al. [67] analyzed previous methodologies for selecting the best available technologies (BATs) for sustainable practices and subsequently developed a methodology for doing so. The authors found that sensitivity analysis should be applied more broadly in BAT assessment methodologies, not solely in the weighting stages. Also, they posited that decision makers should form multidisciplinary teams to remove bias from weighting criteria.

2.5.2 Sustainability Practices in the Chemical Industry

While the focus here is on sustainable manufacturing process characterization, such efforts are not limited to discrete part manufacturing. Reviews of sustainability practices in the chemical industry are also reported, since sustainable process characterization is applicable to chemical processes. The reason is that fundamental, manufacturing-process-analysis concepts were derived from chemical-process analysis [31], Relevant concepts involve the analysis of product creation via discretizing a process flow into unit steps, modeling the processes individually, and aggregating the results to analyze the system holistically. Anastas and Zimmerman [68] developed twelve principles of green engineering, applicable to manufacturing, that were extended from green chemistry. Allen and Shonnard [69] instruct chemical engineering students on environmentally conscious chemical-process design utilizing sustainable process characterization tools. They describe sustainability analysis using principles of unit process modeling, green chemistry, flow analysis, cost accounting, industrial symbiosis, and product evaluation using LCA.

Cano-Ruiz and McRae [70] reviewed approaches for incorporating environmental issues as cost tradeoffs into the design of chemical processes. Among the needs identified, the most important was a change in attitude to view the environment as an objective and not as a constraint. Marteel et al. [71] stated that evaluation of an entire production operation is needed to minimize overall process hazards. They identified needs for research into processes based on catalysts that enable selective chemistry, deactivation of catalysts, use of benign reaction solvents, and simplified separation operations. Jenck et al. [48] claimed that sustainable industrial chemistry had already been implemented in engineering curricula and commercial practice. The authors found investment in new technology to be the largest economic and regulatory hurdle, and identified several focus areas for future work including industrial biotechnology and new process development (e.g., new reactor configurations). Jiménez-González et al. [49] described the top six green- chemistry research areas identified by the American Chemical Society (ASC) Green Chemistry Institute (GCI) Pharmaceutical Roundtable in 2005: continuous processing, bioprocesses, separation and reaction technologies, solvent selection, recycling and optimization, process intensification, and integration of LCA. Nikolopoulou and Ierapetritou [72] reviewed sustainable chemical supply chains, in the areas of energy conservation, waste management, and water management. They identified several challenges, including numerical difficulties during simulation and optimization, development of stochastic models for environmental impacts, and, definition of performance measures for supply chains.

2.5.3 Manufacturing Process Characterization

Prior research has investigated unit manufacturing processes (e.g., machining and injection molding) under the lens of sustainability. Since there are myriad types of manufacturing processes, many of which have been investigated, Kellens [73] performed a review of many studies, the intent is not to review these studies here. In general, the studies have focused on process modeling of specific phenomena and do not generalize to methods that facilitate sustainability characterization. Ehmann et al. [52], for example, examined modeling of dynamic cutting forces in machining processes. They observed that disparate models arise from the availability of numerous methods and that future work will add modeling complexity due to the incorporation of more machining phenomena. Similarly, Guo et al. [53] analyzed machining processes and material modeling for hard metals including steel, titanium, and nickel alloys. They identified future work in microscale and nanoscale machining modeling, stress analysis and prediction, and new computational methods to reduce analysis time. Dixit et al. [54] generalized process modeling into three steps: representation of process mechanics analytically, material behavior modeling, and development of the solution method. Future work needs included expanding models for multi-scale modeling and development of hybrid computational methods.

As alluded to above, manufacturing processes throughout industry can be improved to reduce environmental impacts and improve sustainability performance. Jayal et al. [51] reviewed modeling and optimization for sustainable manufacturing products, processes, and system levels. Examples included dry, near-dry, and cryogenic machining of various metals. Needs identified included rapid assessments for optimal product design and development of hybrid models to reduce required data while maintaining quality results.

To support LCA of manufacturing processes, Duflou et al. [50] identified several shortcomings of traditional LCA including three critical false assumptions: that impacts of the manufacturing-life-cycle phase of a product is negligible, that the machine energy usage is constant, and that LCA neglects the different auxiliary equipment used on each machine. They analyzed process-life-cycle inventories and reported that the assessment method developed by the Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) Initiative addresses several of the shortcomings by creating detailed analyses of manufacturing processes.

To support process-energy analysis, Defraeye [55] reviewed advanced computational modeling approaches for drying processes. The article focused on porous materials (food), and identified needs for multi-scale and material properties modeling along with incorporation of models into a software platform. Mani et al. [20] assessed the current practices for sustainability analysis of manufactured product and determined that current methods are *ad hoc* and do not account explicitly for manufacturing processes. They focused on environmental aspects and reported prior manufacturing process classifications, sustainable manufacturing indicators, computable metrics, information models, and software tools. In addition, they documented an approach to facilitate sustainability characterization for manufacturing processes. Given the existing disparate work in manufacturing-process analysis, as well as the infancy of process sustainability characterization, the following sections strive to identify terms and harmonize their definitions in support of sustainable manufacturing assessment, using the procedure described above.

2.5.4 Summary of Papers Used for Term Definitions

The references used to define terms were derived from a variety of research areas, which included life cycle assessment and management, sustainable process modeling, sustainable chemistry, sustainable policy, organizational standards, and process planning.

The terms have been previously defined by various research domains, but harmonized definitions have not emerged. Tables 2.1-2.6 provide cross references for the references used to define specific terms. The terms have been categorized into six groupings as shown in Figure 1: Scope, Boundary, Material, Measurement, Model, and Flow.

2.6 Discussion of Terminology

The terms that we define herein are derived from literature and from multiple references where possible. There were explicit definitions for each term in those references, although not all definitions for a single term were found to be the same. For these terms, harmonized definitions were created based on the notions from Block [74]. Those notions say that many terms have vague meanings and each author's use has different connotations, until formal definitions are made. Our approach for creating harmonized definitions begins by identifying the most encompassing and relevant definitions for each term. This was accomplished by 1) adopting one definition directly from a source or, when that is not possible, 2) creating a harmonized version that references the other definitions. Where definitions were referenced directly, little to no discussion is included below; the quoted definition is reported in the corresponding table within each category.

In other domains, such as the chemical industry as discussed above, terms that have been defined as synonyms may have different definitions. For example, manufacturing, processing, and production are defined as synonymous, but have subtle differences. Manufacturing can involve the creation of discrete products, whereas processing is a sequence of chemical unit operations to produce continuous or batches of product. Production can encompass both manufacturing and processing. Similarly, a unit operation and a unit process can be distinct [11]. A unit operation is a basic physical operation (e.g., reaction, separations, mixing, heating, cooling, fluid transport, mass transfer). A unit process is identified to involve a chemical conversion (e.g., oxidation, reduction, esterification).

The terminology was categorized into six groupings (Figure 2.1) with the expressed intention to convey the different concepts of sustainable-manufacturing process characterization. Here is a brief summary of the six. More details can be found in the ensuing sections.

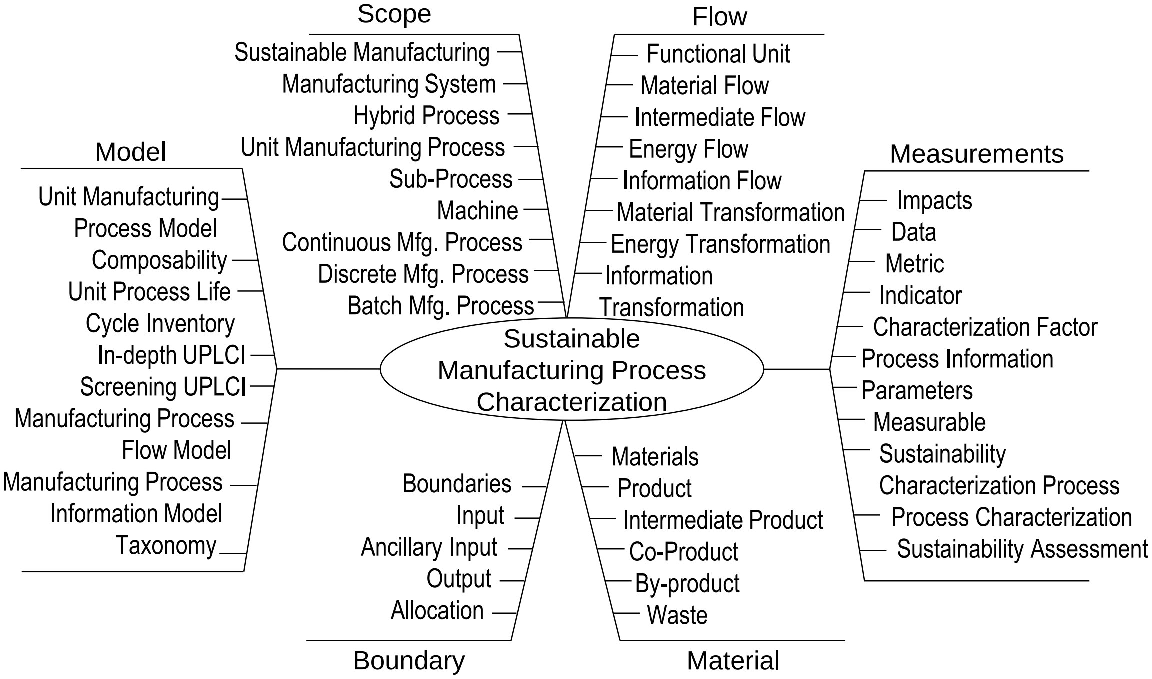

Figure 2.1: Categorization of identified Terminology for definitions.

First, Scope terminology helps to identify the overall goal of a sustainability study. Next, Boundary terminology is used to clarify the input and output flow modeling boundary conditions. Third, Material terminology specifically relates to the physical media related to manufacturing a product. Fourth, Measurement terminology relates to the quantitative values for the sustainability assessment. Next, Model terminology describes or classifies different models. Finally, Flow terminology is used to describe the manufacturing system steps. Terms were organized using an evolutionary method; categories that were changed, merged, or dropped included Data, Decision, Policy, Process, and Product. In some cases, when the terms did not fit well into a specific category, the best fit was selected; for example, *allocation* is included in the Boundary category, *functional unit* is included in the Flow category, *sustainable manufacturing* is included in the Scope category, and *characterization factor* is included in the Measurement category.

2.6.1 Scope Terminology

The Scope terminology helps identify a UMP and what type of production environment is being examined. The terms within the Scope terminology include: *sustainable manufacturing*, *manufacturing system*, *hybrid process*, *unit manufacturing process* (*UMP*), *sub-process*, *machine*, *continuous manufacturing process*, *discrete part manufacturing process*, and *batch manufacturing process*. The terms are discussed below. Table 2.1 summarizes the harmonized definitions of the Scope terminology, including relevant synonyms.

2.6.1.1 Sustainable Manufacturing

Sustainable is defined as "state of the global system, including environmental, social, and economic aspects, in which the needs of the present are met without compromising the ability of future generations to meet their own needs" [75], [76]. *Manufacturing* is defined to be the creation of products, goods, and services (Mani et al., 2014; US Department of Commerce 2013; Zhang et al., 2014) using a system of processes [56], [77], [78]. *Sustainable manufacturing* comes about by addressing the product or process comprehensively. This would include the conservation of energy and natural resources, safety for employees and surrounding communities, and economic viability [20], [24], [56], [78]. These three examples fall neatly into the three pillars of sustainability: environmental, social, and economic [77]. See Table 2.1 for the definition of sustainable manufacturing, and other scope terms.

2.6.1.2 Manufacturing System

A *manufacturing system* contains unit processes, activities, and devices [34], [77], [79]–[81]. Several authors noted that the processes are organized in sequence [34], [79], while others reported that the processes are interrelated [77], [81]. Finally, many authors stated that a transformation occurs [77], [81], causing the inputs to become the outputs. Manufacturing system is synonymous with process system, a term which is often used in the chemical industry.

2.6.1.3 Hybrid Process

Hybrid processes were recognized by Duflou et al. [79] and the term is included here because of the uniqueness of these processes. A hybrid process can be described as a combination of processes completed on a single machine [79]. This is distinguished from a manufacturing cell, where multiple machines in close proximity are utilized in sequence to complete a series of operations. Like a manufacturing cell, however, each process within a hybrid process can be analyzed separately [79]. Notably, a hybrid process is dissimilar to a unit manufacturing process with integrated support equipment, as defined in Section 2.6.1.4.

2.6.1.4 Unit Manufacturing Process (UMP)

A *unit manufacturing process (UMP)* is identified with two common themes. The first considers that the UMP is the smallest element in manufacturing [77], [81], also called individual steps [15], [20]. This first consideration provides a definition for the term “unit.” The second consideration identifies a transformation, either from inputs to outputs [15], [20], [34], [81], adding value [15], [20], or more specific shape, structure, or property transformations [20], [36]. Unit manufacturing process is synonymous with unit operation, a term often used in the chemical industry [82], [83].

Overcash and Twomey [36] noted that UMPs are generally interchangeable, meaning that processes accomplishing the same function can be replacements for each other. The differences in functionality between different UMPs were not addressed directly prior research, but some authors addressed the differences indirectly through mention of transformations. Thus, identification of different taxonomological transformations was included for this definition. The definition in Table 2.1 also addresses that UMPs use various forms of technology, such as one or multiple machines. Although it is the smallest element in manufacturing transformations, there are instances where multiple machines are used to accomplish one activity, but dissecting the process further reveals no more underlying transformations.

2.6.1.5 Sub-Process

A *sub-process* is recognized to be a sub-level of a UMP [20]. Note that sub-processes do not perform recognizable taxonomological transformations, whereas processes do. This characteristic helps to distinguish that a sub-process acting within a process is different from a process within a hybrid process. A sub-process is also distinguished from a machine, since a sub-process activity can be completed without a machine or with one or several machines.

2.6.1.6 Machine

A *machine* performs a unit process [79]. A machine is identified to be a device that performs work or makes work easier, and is a combination of rigid bodies that usually overcome a resistant force [84]–[86]. Synonyms include device, equipment, mechanism, and instrument. Support equipment that does not actually perform the unit process is also included in the definition. Machine is defined here to separate the meaning from a UMP or sub-process, since each UMP or sub-process may require several machines. For example, a penetrant testing process requires the use of a penetrant delivery mechanism, a powder delivery mechanism, a drying mechanism, and an ultraviolet emitting lamp for inspection. Similarly, the common three-axis milling machine has four motors: one for each axis and one for the spindle. While the milling machine is considered a machine, each motor can also be defined as a machine. The UMP can consist of several machines located in close proximity to form a manufacturing cell, or can be embodied within a single, monolithic machine that would convey parts through each stage in the process.

Table 2.1: Scope Terminology

Term	**Synonyms**	**Harmonized Definition**	**Contributing References**
Sustainable Manufacturing	sustainable production, sustainable processing	The creation of goods or services using a system of processes that simultaneously addresses economic, environmental, and social aspects in an attempt to improve the positive or reduce the negative impacts of production by means of responsible and conscious actions.	[20], [24], [56], [77], [78]
Manufacturing System	process system, process stream, production system, line, cell, multi-machine system, multi-machine ecosystem	An interrelated set or sequence of processes that transforms natural and human resources into products.	[15], [20], [24], [56], [77], [78]
Hybrid Process	hybrid workstation	A combination of multiple unit processes into a single machine. These processes can be analyzed separately, but do not include unit processes with integrated support equipment.	[79]
Unit Manufacturing Process (UMP)	unit operation, unit process, process, operation	The smallest elementary manufacturing activity required for a specific taxonomological transformation and composed of machines, devices, or equipment.	[15], [20], [34], [36], [77], [81]–[83]
Sub-process		An element of a unit manufacturing process (UMP) that can be considered auxiliary to the UMP. Similar to a UMP, a sub-process requires resource inputs and generates resource outputs; these inputs and outputs flow from one sub-process to the next within the UMP.	[20]
Machine	device, equipment, mechanism, instrument	A device, piece of equipment, mechanism, or single machine which performs an elementary action or is used for an elementary activity. Furthermore, it is a combination of rigid bodies that performs work or makes work easier.	[79], [84]–[86]
Continuous Manufacturing Process	continuous process, continuous UMP, continuous operation	"Production processes in which the output can be identified and is measurable by mass or volume as in process industry rather than in distinct units."	[79]
Discrete Part Manufacturing Process	discrete process, discrete part process, discrete UMP	"Production processes in which the output can be identified and is measurable in distinct units rather than by mass or volume as in process industry."	[79]
Batch Manufacturing Process	batch process, batch UMP, batch operation	A simultaneous batch process, where components are produced simultaneously, e.g., a heat treatment process, rather than sequentially. Batching occurs in the processing of the materials rather than during material transport.	[87]

2.6.1.7 Continuous Manufacturing Process

Continuous manufacturing process was defined using the definition of Duflou et al. [79].

2.6.1.8 Discrete Part Manufacturing Process

Discrete part manufacturing process was defined using the definition of Duflou et al. [79].

2.6.1.9 Batch Manufacturing Process

A *batch manufacturing process* recognized here is one that processes several products at the same time [87]. This is different from the common batch queuing system, where products are transported or loaded as a batch, which are then processed individually. Hopp and Spearman [87] referred to this as a true batch workstation. Batch processing occurs in the chemical industry as well, where a discrete volume or mass of the chemical is processed in a batch.

2.6.2 Boundary Terminology

During sustainability assessment, identifying the system boundaries is necessary, not only for immediate decisions made from the study, but also to facilitate future studies and comparisons. Boundaries are needed to guide the decision-making process e.g., an injury rate can be associated with one machine in a multi-machine process and can muddle the results for an assessment of the whole process. Terms included within the Boundary category include: *boundaries*, *input*, *ancillary input*, *output*, and *allocation*. Table 2.2 summarizes the harmonized definitions of the Boundary terminology.

2.6.2.1 Boundaries

Boundaries are identified by 1) criteria [77], [81], 2) level of detail of the investigation [34], [50], [78], 3) inputs and outputs [34], [50], and 4) a specific goal for investigating, measuring, or studying some system [34], [50], [77], [78]. Notably, several authors specify well-defined boundaries before examining a unit process using their method [34], [50], [79]. Doing so creates highly compatible process models, and this type of standardization should be helpful for model composability.

2.6.2.2 Input

An *input* is identified as a product, material, energy, or work [46], [81] that enters a unit process [81]. Note that product inputs can be products, intermediate products, co-products, or by-products. The authors would like to recognize that information or knowledge, e.g., in the forms of signals and controls, also enter the defined boundaries. A boundary can range from one process or machine to an entire manufacturing system. Thus, the definition was expanded to include information that enters the boundary of the system under study. The *McGraw-Hill Dictionary of Scientific and Technical Terms* [85] identifies inputs as resources converted by a system, but it should be noted that all inputs that enter a process might not be converted as a result of the process. An example of some non-converted input might be cyclically used water or coolant given that it does not become dirty or leave the system, or possibly machine settings which are input and used for control but are not converted into a feedback output.

2.6.2.3 Ancillary Input

Ancillary input was defined using the definition of ISO [81].

2.6.2.4 Output

Haapala et al. [46] and ISO [81] defined an *output* as a product, material, or energy that leaves a unit process. Since the boundaries of a sustainability assessment can range from one process or machine to the entire manufacturing system, the definition was expanded to be that which leaves the system boundary, as in the definition for *input*, above.

Table 2.2: Boundary Terminology

Term	Synonyms	Harmonized Definition	Contributing References
Boundaries	system boundaries	A set of criteria specifying the scope of a study that identifies the level of detail, e.g. machines, sub-processes, processes, manufacturing system, inputs, outputs, and flows included in the study. Set boundaries are used to identify the extent to which an assessment starts and stops. Studies with specific boundaries can be used in unison to perform more vertical assessments.	[34], [50], [77]–[79], [81]
Input		Products, material, energy, or information that enters the boundaries of the defined system. Includes co-products, by-products, intermediate products, raw materials, or any upstream material flow.	[46], [81]
Ancillary Input		“Material input that is used by the unit process producing the product, but which does not constitute part of the product.”	[81]
Output		Products, material, energy, or information that leaves the boundaries of the defined system. Includes co-products, by-products, intermediate products, emissions, effluents, and wastes which enter other industrial or natural systems.	[46], [81]
Allocation		“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.”	[81]

2.6.2.5 Allocation

Allocation was defined using the definition of ISO [81]. While the *McGraw-Hill Dictionary of Scientific and Technical Terms* [85] states, “to assign a portion of a resource to an activity,” the ISO definition was selected because it is more applicable to UMP characterization.

2.6.3 Material Terminology

Material terminology is used to identify any *material*, *product*, or *waste* that flows into or out of a process (Sections 2.6.3.1-2.6.3.6). This includes any *material* that is used in a *unit manufacturing process,* and any *product* or *waste* that the process generates. These are fundamental to *impact*, *allocation*, and *functional unit* identification. Table 2.3 presents the harmonized definitions of Material terminology.

2.6.3.1 Materials

Raw materials are described as *materials* that are used to produce a product [77], [81]. These are defined as primary (non-recycled) or secondary (recycled) materials [81].

Zhang et al. [77] described raw materials as physical components extracted from the ecosystem and processed into another form of matter to be later used. Most manufacturing does not use materials that come directly from the ecosystem. Thus, the term *materials* was selected to define physical materials from upstream processes, rather than the term raw materials, to remove this implication. Finally, materials can also be auxiliaries, such as solvents and catalysts, and additives; and they can be renewable or recycled.

2.6.3.2 Product

Product was defined using the definition of Zhang et al. [77].

2.6.3.3 Intermediate Product

Intermediate product was defined using the definition of ISO [81].

2.6.3.4 Co-Product

Co-product was defined using the definition of ISO [81]. Additional discussion is provided in Section 2.6.3.5.

2.6.3.5 By-Product

By-products of a process may be generated as a result of the desired reaction stoichiometry, a consequence of undesired secondary reactions, or when separating systems (distillation columns). For example, pollutants can be viewed as by-products of a UMP in the form of unrecovered materials and emissions [70]. By-product composition is worth considering when evaluating the tradeoffs between different processes. For example, considering the reactivity, toxicity, and mass of by-products simultaneously yields a more objective analysis than considering them independently. Lowe [88], on the other hand, posited that by-products should be reduced at the source when possible, rather than creating markets for dealing with them. For example, Turton et al. [89] noted that, within an industrial park, a by-product is an unwanted resultant stream "that cannot be sold for an overall profit." Taking this view of by-products means that they must be avoided during design, planning, and decision making because by-products are often due to inadequate design or inefficient practices and result in economic losses or environmental impacts for the manufacturer.

In comparison, co-products are useful in some regard and are not considered by-products or waste (see below). Many metallic materials are produced as co-products of other metals processing. For example, cadmium, indium, germanium, and gallium are co-products of zinc production from the mineral sphalerite [90]. The metals produced are commonly recovered from by-products of zinc production and arise from impurities in the constituent mineral.

Table 2.3: Material Terminology

Term	**Synonyms**	**Harmonized Definition**	**Contributing References**
Materials	raw materials	Any physical material used to produce a product. Primary material includes the material from initial extraction and processing, and secondary material includes recycled content which has undergone reprocessing.	[77], [81]
Product		"Any good or service offered to serve the needs of other members of society."*	[77]*, [81]
Intermediate Product		"Output from a unit process that is input to other unit processes that requires further transformation within the system."	[81]
Co-product		"Any of two or more products coming from the same unit process or product system."	[81]
By-product		An undesired material, in any phase (gas, liquid, solid), output from a unit process that results in economic losses or environmental impacts.	[70], [88], [89]
Waste	emissions, effluents	"Substances or objects which the holder intends or is required to dispose."*	[77], [81], [91]*

2.6.3.6 Waste

Waste was defined using the definition of ISO 14040 [81], which in turn used the definition from the Basel Convention [91]. Emissions and effluents are included as synonyms because these are also of no value to the holder and are usually disposed or released at some cost (e.g., handling or permitting costs).

2.6.4 Measurement Terminology

Measurement terminology addresses the differences between reporting mechanisms, Sections 2.6.4.1-2.6.4.7 address numerical values, whereas Section 2.6.4.8-2.6.4.11 address the process. A *sustainability assessment* is performed to identify the different *impacts* of a process, system, product, or service. Reporting these impacts are performed using *data*, *metrics*, and *indicators*. These are three reporting mechanisms, where *data* are the raw measurement values, *metrics* are a unit of measure used for evaluation, and *indicators* are meaningful quantitative representations that are used to normalize a set or array of metrics using a *characterization factor*. The three reporting mechanisms are generally different from *process information* and *parameters* because the latter usually directly reveal little about the sustainability of the process. Nevertheless, they can indirectly influence sustainability assessment results. The term *measurable* was included because it is important for the results of a sustainability study to be a quantified entity. The last three terms differentiate a *sustainability characterization process*, a *process characterization*, and a *sustainability assessment*. Table 2.4 presents the harmonized definitions of measurement terminology.

2.6.4.1 Impacts

Impacts was recognized to be a term integral to manufacturing process characterization because of its frequent use in definitions developed for the terminology herein. ISO [81] noted that quantifiable impacts or consequences of process inputs and outputs on human health and the environment can be organized into various impact categories. Zhang et al. [77] identified economic, environmental, and social weltanschauungen (world views) as different impact domains. Zhao et al. [92] noted that environmental impacts of products must be reduced through manufacturing process analysis. The definition for impact is generalized to include both positive benefits and negative detriments. All impacts arise as a consequence of the manufacturing process and can occur on both long and short time scales. Positive impacts include economic, environmental, or social aspects - cost savings, pollution reduction, and job creation, to name a few. Negative impacts include reduction of local supplier use, increased water effluents, and increased job hazards.

2.6.4.2 Data

Data was defined using the definition of Veleva and Ellenbecker [78].

2.6.4.3 Metrics

Metrics are used to track or calculate indicators [24], [78], and can be used to describe the sustainability performance of a system [46], [93]. Different types of evaluation criteria, e.g., midpoints/endpoints and metrics/indicators are used at different levels of system analysis. Due to the associated level of detail, higher-level criteria become abstracted from the process settings as the system analysis broadens. Thus, broader system analysis tends to provide less specific guidance to lower-level solutions. Meaningful values for different decisions are dependent on the abstraction of the decision from the context of the analysis. Metrics are less abstracted than indicators, and will lead to more direct manufacturing process solutions.

For example, to calculate a metric for normalized waste per unit product, the data collected depends on the type of waste and could be computed either in terms of volume of waste produced per unit time or mass of waste per unit time. An example indicator (Section 2.6.4.4) calculated from the waste metric is human toxicity potential, which can be measured using disability adjusted life years (DALYs). DALY is the sum of the average years of life lost and average years lived with a disability [94]. In this example, the metric results provide decision direction whereas the indicator results are inherently opaque and create an interpretation conflict. A higher waste metric value would give the direction to reduce process waste. Whereas a higher indicator value (increased human toxicity potential) may be due to increased waste, increased aerosol by-products, or a change in workpiece material type, and does not provide process-specific guidance. To summarize, identifying the better of two alternative processes can be completed with any number of selected criteria using multi-criteria decision analysis (MCDA). But identifying improvement opportunities for a specific process would require more selective criteria.

2.6.4.4 Indicator

An *indicator* is a criterion or measure used to quantify information to describe a phenomenon or aspect of a system for business or engineering decision makers [20], [24], [77], [78], [81]. Sets of indicators are commonly used to collectively measure sustainability [24], [95].

2.6.4.5 Characterization Factor

Characterization factor was defined using the definition of ISO [81].

2.6.4.6 Process Information

Process information is recognized to be the information related to a UMP [17], [96]. Overcash et al. [96] included the functional unit, time period, geography, and technology, whereas ASTM [17] included part geometry, key performance indicators (KPIs), material properties, setup and operation instructions, quality plans, and control programs as process information. Process information is a generalized term that includes all information relating to the process and/or process-product interaction.

Table 2.4: Measurement Terminology

Term	**Synonyms**	**Harmonized Definition**	**Contributing References**
Impacts	sustainability results	The results or outcomes of an assessment or study that quantify social, economic, and environmental consequences and which are described and identified using data, metrics, or indicators. Impacts can be both positive and negative.	[77], [81], [92]
Data	measurements	"Actual measurements of observations of a variable."	[78]
Metric	measure, performance metric, performance measure, midpoint	A unit of measure used in evaluating a system, machine, process, or sub-process. Metrics are used to calculate an indicator. A variety of metrics are commonly used to assess the economic, environmental, and social aspects of sustainability. Metrics are selected and evaluated based on end user needs and the scope or level of assessment.	[24], [46], [78], [93]
Indicator	impact category, category indicator, key performance indicator (KPI), composite indicator/index, endpoint	A meaningful variable or parameter that describes or provides information about a process or manufacturing system. Multiple indicators are typically used for an evaluation. Metrics are used to calculate an indicator.	[20], [24], [77], [78], [81]
Characterization Factor	conversion factor	"Factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator. The common unit allows calculation of the category indicator result."	[81]
Process Information		Description of the unit process and description of the product relating to that process, this includes any information related to the product or process in reference to the functional unit and that process.	[17], [96]
Parameters	variables	Conditions, attributes, or settings of a manufacturing process that can be varied to affect the process and performance of that process.	[24], [34], [78]
Measurable		"Capable of being measured quantitatively or qualitatively in multi-dimensional perspectives, e.g., economic, social, environmental, technical, etc."	[24]
Sustainability Characterization Process	sustainability measurement process	"A sequence of operations, with the necessary instruments and tools and having the objective of determining the value of an indicator."	[20]
Process Characterization	production process characterization, process sustainability characterization	"A process characterization activity typically identifies key inputs and outputs of a process, collects data over the entire operating range, estimates the steady-state behavior at optimal operating conditions and builds models describing the parametric relationships across the operating range. A process characterization activity results in a set of mathematical process models that can be used to monitor and improve the process."	[20]
Sustainability Assessment	sustainability analysis, sustainability study, system performance analysis	A methodological examination of a system, process, or product undertaken to understand the associated economic, environmental, and social impacts, with respect to a specific scope and time scale.	[77], [81], [97]

2.6.4.7 Parameters

Parameters and variables are described as conditions of a UMP input [34], attributes of a system [78], or measured properties [24]. Parameters are a specific kind of process information.

2.6.4.8 Measurable

Measurable was defined using the definition of U.S. Department of Commerce [24].

2.6.4.9 Sustainability Characterization Process

Sustainability characterization process was defined using the definition of Mani et al. [20].

2.6.4.10 Process Characterization

Process characterization was defined using the definition of Mani et al. [20].

2.6.4.11 Sustainability Assessment

Sustainability assessment is included due to its frequency of use within the discussion of this article. It is defined as a consequence of broadening the concept of life cycle assessment to include social and economic impacts. Zhang et al. [77] identified several contributing assessment methods including social impact assessment, environmental impact assessment, and lifecycle costing. Each of these methods can be included under the umbrella of sustainability assessment. Ness et al. [97] identified three elements pertinent to the definition of sustainability assessment: 1) integration of nature and society, 2) spatial aspects, and 3) temporal aspects.

2.6.5 Model Terminology

Model terminology addresses the different types of models commonly found in unit manufacturing process characterization. General model types have been defined already, and it is not the intention of the authors to include all possible models or equations that can be used for characterization, e.g., specific relationships such as the Navier-Stokes equation are not discussed. The terms included here are *unit manufacturing process model*, *unit process life cycle inventory*, *in-depth UPLCI*, *screening UPLCI*, *manufacturing process flow model*, and *manufacturing process information model*, Sections 2.6.5.1 and 2.6.5.3-2.6.5.7. Two other terms included are *composability* (Section 2.6.5.2), which describes model interaction, and *taxonomy* (Section 2.6.5.8) which defines different unit manufacturing processes by function. Table 2.5 presents the harmonized definitions of the Model terminology.

2.6.5.1 Unit Manufacturing Process Model

Unit manufacturing process models are developed to explore process and material interactions, and can be used to quantify sustainability metrics [80]. The models are used to relate material and energy inputs to outputs and can account for variations in the process [93]. Models are developed through mechanistic relationships or empirical observation [80]. Model evaluation allows for analysis of product and process designs and investigation for improvement [93].

2.6.5.2 Composability

Composability was defined after Davis and Anderson [98]. One goal for unit manufacturing process modeling is the ability to chain different UMP models together to create a manufacturing system or product assessment. Automated manufacturing-process-flow planning and manufacturing system optimization using process control can occur given that models can interact with one another. This interaction between models is termed *composability*.

2.6.5.3 Unit Process Life Cycle Inventory (UPLCI)

A *unit process life cycle inventory* (UPLCI) contains data resulting from a sustainability study [35]. UPLCI was defined using the definition of Overcash and Twomey [36]. UPLCIs are formatted to contain an overview of the process, literature data and references, a parameter selection of the process, LCI energy calculations, and LCI mass loss calculations [99]. UPLCI construction has been formalized in the CO2PE! Method, which can be used to generate UPLCIs using either the in-depth approach (Section 2.6.5.4) or the screening approach (Section 2.6.5.5) [35].

2.6.5.4 In-Depth UPLCI (CO2PE!)

The *in-depth UPLCI* approach of the CO2PE! method generates more accurate UPLCI data than the screening approach [35]. The approach is divided into four studies: time, power, consumables, and emissions studies [34], [35], [79]. The studies document all relevant process inputs and outputs in detail [34], [35].

2.6.5.5 Screening UPLCI (CO2PE!)

The *screening UPLCI* approach of the CO2PE! method generates UPLCI data and provides a first insight into a UMP [35]. A screening study would be considered as an initial investigation into a UMP and would contain boundaries, a functional unit, machine parameters, and process information [34]. This information is used to generate energy and mass loss calculations [34], [35], [79].

2.6.5.6 Manufacturing Process Flow Model

Manufacturing process flow model was defined using the definition of Mani et al. [20].

2.6.5.7 Manufacturing Process Information Model

Manufacturing process information model was defined using the definition of Mani et al. [20].

Table 2.5: Model Terminology

Term	**Synonyms**	**Harmonized Definition**	**Contributing References**
Unit Manufacturing Process Model	unit process model, UMP model	Several mathematical models developed for a specific unit manufacturing process to evaluate a particular set of metrics or indicators. Models can be developed from mechanistic relationships or empirical measurement and observation. Models should account for all inputs and outputs of the process.	[80], [93]
Composability		The capability to select and assemble models in various ways to represent a process flow, or the capability of the models to represent different process scales. Models can be individually or combinatorially assessed to identify the impacts at different levels of production, e.g., a sub-process, a unit manufacturing process, or a manufacturing system.	[98]
Unit Process Life Cycle Inventory (UPLCI)		A process characterization reporting framework that contains data, equations, results, an example for a specific process and functional unit interaction, and references. Data includes process descriptions, figures, pictures, energy calculations, and physical and energy property tables. Equations calculate mass loss and energy requirements using ancillary inputs and process information. The example of the UPLCI is for a specific workpiece, process, or machine.	[34], [36], [99]
In-depth UPLCI (CO2PE!)	in-depth systematic inventory analysis, in-depth approach	A process characterization method that includes four studies of a specific machine: time, power, consumables, and emissions. Results in materials and energy input and output (LCI) data of a unit manufacturing process utilizing that machine. Can be considered a method to develop unit process models.	[34], [35], [79]
Screening UPLCI (CO2PE!)	screening systematic inventory analysis, screening approach	A process characterization method that approximates LCI input and output data using representative energy calculations and mass loss calculations reported in literature. Can be considered a method to develop unit process models.	[34], [35], [79]
Manufacturing Process Flow Model		"Describes the dataflow (e.g., inputs, outputs, reference and control flows) and precedency in manufacturing processes. An example is the Systems Integration for Manufacturing Applications (SIMA) reference architecture. The data flow in activity models can be entities in information models."	[20]
Manufacturing Process Information Model		"Defines relationships between sustainability performance and information related to manufacturing processes (e.g., resources, tooling materials, and energy). Defines entities and their relationships. Can include multiple levels, e.g. class or property, and can include mathematical representations."	[20].
Taxonomy	manufacturing process taxonomy	An ordered manufacturing process classification used to identify specific unit manufacturing processes by their function or attributes.	[20], [79]

2.6.5.8 Taxonomy

A manufacturing process *taxonomy* is used to categorize a wide variety of manufacturing process [79]. A taxonomy also helps engineers and other manufacturing personnel to understand the available processes and to identify methods to manufacture products [20]. Finally, taxonomies help convey information for manufacturing decision making [20]. Examples include taxonomies defined by the NRC [15], Todd et al. [13], and DIN 8580 [18]. An in-depth comparison of manufacturing process taxonomies was performed by Mani et al. [20]. Taxonomies for the chemical industry either identify the equipment types (e.g. [82], [83], [100]) or are organized by the specific chemical product, but these taxonomies are not mirror equivalent to those found for unit manufacturing processes.

2.6.6 Flow Terminology

Flow terminology defines movement of energy, materials, and information within a manufacturing system. Flows are normalized to a *functional unit* (Section 2.6.6.1), and are identified by three main types, *material flow*, *energy flow*, and *information flow* (Sections 2.6.6.2-2.6.6.5). Fundamental to these flows are the different ways in which they are transformed from one form to another; i.e., *material transformation*, *energy transformation*, and *information transformation* (Sections 2.6.6.6-2.6.6.8). The flow definitions below describe discrete material, energy, or information inputs and outputs flowing between UMPs. The transformation definitions below describe the conversion of material, energy, or information inputs within the UMPs to form the outputs. The flows define the quantity of the material (e.g., kg or L), the energy (e.g., J), or the information (e.g., bytes) and should not be construed with processing rates (e.g., kg/s or L/s), energy consumption rates (e.g. W), or information transfer rates (e.g., baud). Table 2.6 presents the harmonized definitions of Flow terminology.

2.6.6.1 Functional Unit

A *functional unit* is recognized to be a qualitative and quantitative reference unit of a manufacturing system [34], [81], [96]. For a manufacturing system, the functional unit is a quantity of a product that flows through a production system over a specified period of time and serves to act as a denominator for all process performance measures that are used to evaluate the performance of any UMP in a manufacturing process flow. For a UMP, a functional unit is a quantifiable and qualifiable reference unit indicating the performance of a unit process [34], and it can include volume or mass of material removed, available oven capacity, and flow rate of a chemical process, among other measures. CO2PE! specifies standard functional units to maintain normalized UPLCI data for various processes [34].

2.6.6.2 Material Flow

Material flow was defined using the definition of ISO [81].

2.6.6.3 Intermediate Flow

Intermediate flow was defined using the definition of ISO [81].

2.6.6.4 Energy Flow

Energy flow was defined using the definition of ISO [81].

2.6.6.5 Information Flow

Information flow was defined using the definition of Mani et al. [20].

2.6.6.6 Material Transformation

Material transformation was defined using the definition of ASTM [17].

2.6.6.7 Energy Transformation

Energy transformation was defined using the definition of ASTM [17].

2.6.6.8 Information Transformation

Information transformation was defined using the definition of ASTM [17].

Table 2.6: Flow Terminology

Term	**Synonyms**	**Harmonized Definition**	**Contributing References**
Functional Unit	reference unit	A qualitative and quantitative reference unit of a manufacturing system or UMP that is used to normalize performance metrics across the manufacturing system or UMP for a specific product.	[34], [81], [96]
Material Flow		"Products entering from or leaving to another product system."	[81]
Intermediate Flow		"Material, energy, or information flow occurring between unit processes of the product system being studied."	[81]
Energy Flow		"Input to or output from a unit process or product system, quantified in energy units. Can be called input or output energy."	[81]
Information Flow		"Inputs, outputs, reference and control flows. Can be entities in information models."	[20].
Material Transformation		Can include mass change, phase change, structure change, deformation, and consolidation.	[17]
Energy Transformation		Can include chemical, electrical, thermal, mechanical, and electromagnetic sources.	[17]
Information Transformation		"Input information undergoes changes that can include efforts such as data reduction, conversion, translation, and augmentation. This could result in changes to items such as production metrics (e.g., throughput and OEE) and environmental metrics (e.g., energy, material, water, emissions, and waste)."	[17]

2.7 Conclusions and Recommendations

A common set of terminology is yet to be developed for researchers, scientists, engineers, and decision makers involved in sustainable manufacturing. Consequently, it is still not possible to communicate sustainable manufacturing process requirements and results across a manufacturing system or enterprise. This work takes a step towards identifying the key terms and definitions as they relate to sustainable manufacturing. Terms were organized into six categories, namely, Scope, Boundary, Material, Measurement, Model, and Flow, to extract overarching concepts. Synonym identification for key terms was completed by reviewing the relevant literature to clarify and harmonize overlapping definitions. A review of literature related to sustainable manufacturing process characterization and modeling was performed to elevate understanding of key concepts and to identify related terminology. The authors observed that a holistic review of research on process characterization and process models in support of sustainable manufacturing is yet to be accomplished; such a review would be beneficial, perhaps by organizing prior work by process type using a standard process taxonomy.

Forty-seven key terms were defined as part of this study. This collection of terms is not exhaustive; it is one step towards identifying and standardizing common terminology for sustainable manufacturing process characterization. This initial set of terminology can stimulate conversations and communication within manufacturing facilities and supply chains to support sustainable manufacturing efforts. It is important to note that normalizing the language through standard terminology and definitions is critical. This work can also initiate community discussions on standards for manufacturing process characterization terminology. Organized discussions could proceed with involvement of researchers and industry practitioners to facilitate consensus on generalized terminology, definitions, procedures, and practice. Such discussions could proceed within small groups (roundtables), conference presentations, panel sessions, or workshops.

Future work includes standardizing the terminology through standards development organizations like ASTM International. Based on the common terminology resulting from conversations among a myriad of industries, a generalized, sustainability-characterization method for manufacturing processes should also emerge. Finally, to ensure eventual industry adoption, methods must be formalized in scalable, composable models and implemented in affordable software applications. Such formalization is needed because 1) sustainability assessment requires a broad set of expertise across multiple disciplines, 2) data collection is tedious, and 3) mathematical calculations, especially for complex products and production systems, are non-trivial. Such software will improve sustainable decisions and real-time control of manufacturing networks. Each aspect of this work will require intensive effort and collaboration on the part of researchers and practitioners representing a broad set of disciplinary and industrial expertise. Completion of this fundamental research will enable applications of sustainable manufacturing process characterization to benefit product improvement, process optimization, and supplier selection activities.

2.8 Acronyms

ASM – American Chemical Society
ASTM – American Society for Testing and Materials
BAT – Best available technology
CO2PE! – Cooperative Effort on Process Emissions in Manufacturing Initiative
CSM – Competitive sustainable manufacturing
DALY – Disability adjusted life years
DIN – German Institute for Standardization
DOC – Department of Commerce
ECMPRO – Environmentally conscious manufacturing and product recovery
ESET – Economic, social, environmental, and technological
GCI – Green Chemistry Institute
IMS – Intelligent manufacturing system
ISO – International Organization for Standardization
KPI – Key performance indicator
LCA – Life cycle assessment
LCI – Life cycle inventory
MCDA – Multi criteria decision analysis

NIST – National Institutes of Standards and Technology
NRC – National Research Council
OEE – Overall equipment effectiveness
UMP – Unit manufacturing process
UPLCI – Unit process life cycle inventory

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2.10 Disclaimer

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CHAPTER 3: A UNIFYING METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF MANUFACTURING PROCESSES

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CHAPTER 3: A UNIFYING METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF MANUFACTURING PROCESSES

3.1 Abstract

In spite of the recent advances in sustainability assessment, design and manufacturing engineers must apply assessment methods and tools in an ad hoc manner. This not only increases the engineering time but also limits the utility of the assessment results. An integrated methodology and practical approach to sustainability assessment is reported. The approach combines the upstream process data along with the models of in-house manufacturing processes to conduct cradle-to-gate product sustainability assessments. By linking individual manufacturing process models to represent a sequential process flow, assessments be can made to support decisions at the product, process, and supply chain level. The utility of the approach is demonstrated using a software prototype tool developed to assist the design for manufacturing efforts for a metal aircraft assembly.

3.2 Introduction

Sustainability is becoming part of the culture throughout the world as consumers buy more eco-friendly products and companies adopt more socially responsible programs. Many initial corporate responsibility programs were implemented in response to the growing energy demands and the related economics of reducing energy and materials use, and improving cost efficiency [101]. Energy consumption in the United States is at an all-time high and will likely continue to grow unimpeded [5] unless steps are taken to address this concern. This energy use is subdivided into residential, agricultural, commercial, transportation, and industrial sectors, with the industrial sector accounting for 31% of total energy use in the U.S. [102], and one third of energy use globally [6].

As demand for commodities grows, companies are responsible for large impacts on society and the environment [103]. In reaction, company perspectives have progressed to integratively account for the three aspects of sustainability in decision making, i.e., economic, environmental, and social [104]. Many leaders realize that setting a standard as a leading organization is beneficial in the marketplace, and have developed rating indices to make comparisons between companies [103], [105]. As companies become more sustainability initiative focused, they require tools to assess different aspects within their organizations. Many sustainability assessment methods [97] and indices [40], [106], have been developed since the publication of the Brundtland Commission Report on sustainable development in the 1980s. But a majority of the methods are used to evaluate sustainability of a nation or a region; these can be limited in their use to product designers because they provide opaque results [107]. The development of new methods should transition to be integrative of all sustainability aspects, thus, researchers and companies should strive to develop holistic assessments that integrate economic, environmental, and social metrics [101].

The goals of the overarching research reported herein are to develop a method for modeling and assessing the sustainability performance of discrete manufacturing processes and to provide a framework for the subsequent use of the modeled processes. Furthermore, a software tool is developed to realize the process modeling, process assessment, and product assessment aspects of the framework; these aspects assist design for manufacturing decision making. The specific objective of the work reported was to develop a unifying method for sustainability assessment of manufacturing processes.

In the following section, the discussion transitions to the background of sustainability assessment for unit manufacturing processes in Section 3.2, including the motivation and substantiating literature. Previous approaches developed are then reviewed in Section 3.3. A new methodology is presented in Section 3.4. A demonstration of the method is provided in Section 3.5. Finally, concluding remarks are given in Section 3.6.

3.3 Background

3.3.1 Motivation

Ness et al. [97] classified sustainability assessment methods into three different categories: indicators/indices, product-related assessments, and integrated assessments. The tool presented in this paper would be classified as product-related assessment because it specifically targets a manufacturing process flow. This classification scheme is limited, however, because more recent assessment methods combine previous approaches to form more holistic methodologies. Product-related assessments from the Ness et al. [97] classification scheme are further subdivided into life cycle assessment (LCA), life cycle costing (LCC), product material flow analysis, and product energy analysis. The tool developed herein and presented below combines several aspects of these methods, thus several related tools are first discussed.

LCA methods and tools have come closer to enabling engineers and supplier managers in making sustainability-related decisions in design, but they do not yet provide detail to support robust engineering decisions. Perhaps the most appropriate use of LCA is for reporting environmental impacts of a product. Although LCA is the most developed assessment method for assisting sustainability assessment, it has significant pitfalls as outlined in the European Environmental Agency’s (EEA) guideline on LCAs [26], [27], [108]. These pitfalls include cost, complexity and long analysis time scales, multiple standards, and subjective judgments, which make LCA studies opaque. Many tools have been developed for LCAs, including GaBi, SimaPro, Quantis, and Earth Smart.

In addition to those for environmental impacts, methods and tools have emerged for assessing specific social impacts. These methods originate from a variety of fields of research, but have not been adequately incorporated into unit process-based sustainable manufacturing assessment. One example, from human factors engineering, considers the NIOSH (National Institute of Occupational Safety and Health) lifting equations [109], which have been implemented into MS Excel [110]. LCA software contains methods for reporting results that include human health impacts. The ReCiPe LCIA method can be used for calculating mid-point impacts on human health, such as carcinogenicity. These calculations are tied to material outputs and are not commonly scaled to process conditions.

Jorgensen et al. [111] argued that environmental impacts have a causal link to processes, while social impacts have a causal link to company conduct. This highlights the complexity of estimating social impacts from a unit process level. Different processes for one company will have different social impacts, e.g., some positions require more skill or are more dangerous than others. Jorgensen et al. [111] also noted that selection of impact categories to measure for a social LCA remains an open question. This will likely be influenced by the type of decision to be made and the system being studied.

Relatively few tools have been developed to address the needs of design engineers during product development. Ramani et al. [29] classified eco-design tools into three categories, checklists, LCA based, and quality function deployment (QFD) based. They claimed that current LCA tools are not design oriented. The two other categories were also deemed as inadequate – checklist tools provide guidelines rather than solutions to design problems and QFD tools are too reliant on the knowledge of the designer [29]. A tool is needed which provides solutions without sustainability knowledge developed by the designer, and, ideally, the tool would teach the designer. Chiu and Kremer have used design stages to classify green design tools, they included eco-design tools in their definition. They claimed information-technology solutions which integrate Design for X concepts into a framework are needed [28].

Currently, there is little investment in sustainability assessment of component manufacturing in the early design stages and, assessment is often limited to energy or material flow analysis, which can be summed up in life cycle inventories (LCIs). LCIs are crucial to sustainable manufacturing today, but contain generalized process data and information [34], [35]. Research is needed to create more tailorable analyses and to integrate triple bottom line analysis with functional decision tools to support design for manufacturing decisions. To address these needs, a methodology has been unified to standardize the process modeling and improvement. A software tool is under development to assist in conducting design and manufacturing phase sustainability assessments, based on mathematical models of unit manufacturing processes. This tool has been presented in previous work [112], and the work herein will focus on the methodology.

3.3.2 Background Literature

The reference literature from unit manufacturing process assessment has a variety of source information available. This section will cover the different references called upon from the previous methodologies presented in Section 3.3. This section will provide references for textbooks, government and international standards, life cycle assessment (LCA), material and energy flow analysis (MEFA), machine measurement, multi-criteria decision analysis (MCDA), process planning, and product design.

The textbooks referenced in literature come from three main domains: chemical engineering, manufacturing engineering, and product design. Those from chemical engineering focus on chemical process design [113]–[115] and chemical process reference texts [116], [117]. Those from manufacturing engineering include texts on materials and manufacturing processes [118]–[122] and reference handbooks [123]–[125]. Product design texts focus on design concepts and material selection [126]–[128]. Common sources also include government and international standards. Commonly referenced governmental standards include those for manufacturing practice [129]–[132], and life cycle assessment (LCA) [133]–[135]. Specific ISO standards commonly referenced include environmental management [136]–[141], automation systems and integration [142]–[144], and energy management [145]. The field crosses life cycle assessment with material and energy flow analysis (MEFA). Of those references to LCA, included are standards [133]–[135], books, e.g., [146]–[148], generalized method papers, e.g., [149]–[151], and product assessment papers, e.g., [152]–[154]. MEFA originates in industrial metabolism and materials accounting, e.g., [155]–[158]. The research originally looked at tracking large scale flows, i.e., city or country wide, of materials and energy. This research evolved into MEFA, e.g., [159]–[161], which investigates measuring and modeling the flows for manufacturing products.

Focusing on modeling specific manufacturing processes to increase the detail of sustainability assessment necessitates collection of high quality data, i.e., the inputs to a study. Most researchers have focused on energy measurement, e.g., [162]–[164], and, while important, measurement of other manufacturing process flows should be undertaken. A related research area is the reporting of evaluation criteria, i.e., the outputs of a study. While the selection of specific criteria is left to the decision maker, researchers have documented the varying attempts to holistically capture sustainability reporting [165]–[169].

Multi-criterion decision analysis (MCDA) is utilized throughout sustainability analysis to simultaneously evaluate the variety of evaluation criteria from the three aspects of sustainability. Common methods include the analytic hierarchy process (AHP), weighted sum method (WSM), fuzzy logic methods, and reverse neural networks, e.g., [170]–[173].

Aside from process redesign or supplementation, two approaches for improving sustainability performance are recognized. The first approach is to select more sustainable processes, e.g., [174]–[178]. The second approach is the design of products, i.e. manufacturing is dependent on product geometry, form, function, and material selection. Research areas include sustainable design concept development [68], [179], design for manufacturing [180], [181], and design for disassembly [182].

3.4 Previous Methodologies

Reviews have been performed by Ibanez-Forez et al. [67], Herva and Roca [183], Mani et al. [20], Kellens [73], Arena et al. [184], and Jenck et al. [48] to identify tools and methodologies useful for businesses for implementation and use of sustainable practices. Haapala et al. [185] identified recent advances in sustainable manufacturing; other authors have focused specifically on the use of life cycle assessment [26], [27], [47]. Other methods have been reported, but descriptions only consisting of modeling steps, e.g. Jiang et al. [186], Duflou et al. [187], Kellens et al. [188], Gutowski et al. [189], Roman and Bras [33], Valivullah et al. [191], were omitted from this review as the goal is to compare the overall assessment methodologies, beyond modeling. Thus, the following review of previous methodologies is an attempt to identify the uniqueness of each assessment method. Following this brief review, a generalized method is presented to unify the ideas of the previous methodologies identified. Incorporating the facets of each method is outside the scope, but providing references will facilitate further investigation by practitioners and researchers. Table 3.1 shows the steps for each method in this review by sorting each step into the generalized steps. Steps are identified by the colored columns, and follow the methodology described in Section 3.4. Numbers identify steps used in each method, and numerical order reflects that found in the reference. The reviewed methods compared to the generalized model deviate in four ways. Having multiple steps to complete one generalized step (e.g., Ibáñez-Forés et al.), combining two generalized steps into one step (e.g., Kellens et al.), reorganizing steps to follow a unique execution sequence (e.g. Sutherland & Gunter), and omitting steps that are assumed or completed prior to beginning the respective method (e.g., missing planning steps).

Table 3.1: Comparison of previous methodologies utilizing manufacturing process characterization

Author	**Year**	**Method**	**DPP**	**SEC**	**IPP**	**MS**	**DCI**	**CA**	**RIA**	**RFDS**	**IEI**
Gonzalez, et al. [31]	2000	GU			1	3, 4	2				
Hendriks et al. [192]	2000	PPA	1,2			4	3		5		
Sutherland & Gunter [193]	2001	PM				3	1	2			
Pun, et al. [194]	2003	CI	1, 2, 3, 4	5			6	7, 8	10	9, 11, 12	13, 14
Hula, et al. [195]	2005	PA			1, 2	3, 4		5	6		
ISO 14040 [81]	2006	PA	1				2	3	4		
Overcash, et al. [99]	2009	GU	1, 2	3		4, 5					
Rodriguez et al. [196]	2011	PPI					1	2	3	4	
NIST/SEMATECH [197]	2012	PM	1				2		3	4	
Kellens et al. [34], [35]	2012	GU	1			2a	2b			3	
Eastlick & Haapala [80]	2012	DC	1	2, 3				4	5, 6		
Jiang, et al. [198]	2012	PI		1				2			3
Thiede, et al. [199]	2012	PI				4	1		2		3
Herva et al. [200]	2012	PPA			1	2		3	4		
Jiang, et al. [201]	2012	PPA					1	2	3		
Zhao et al. [92]	2012	PPI			1, 3, 5			2, 6	4, 7		
Ostaeyen, et al. [202]	2013	PA	1			2	3		4		
Dorr, et al. [203]	2013	PI	1	2, 3			4		5, 6		7
Ibáñez-Forés et al. [67]	2014	AB		1			2	3, 4, 5	6, 7		
Cimino-Hurt & Haapala [204]	2014	NP	1	4	2	3					
Mani et al. (M. 1) [20]	2014	PC		1		2				3	
Mani et al. (M. 2) [20]	2014	DS				2, 3	1			4	
Eastwood et al. [33]	2014	PC	1	2	3	4		5	6		

PM	Process Modeling
AB	Assessing BATs
NP	New Process Assessment
PC	Process Characterization
GU	Generate UPLCI
PA	Product Assessment
DC	Design Comparison
CI	Continuous Improvement
PI	Process Improvement
PPA	Process Plan Assessment
PPI	Process Plan Improvement

DS	Decision Support
DPP	Develop Project Plan
SEC	Select Evaluation Criteria
IPP	Identify Process Plan
MS	Modeling & Simulation
DCI	Data Collection & Inventory
CA	Conduct Assessment
RIA	Results Interpretation & Analysis
RFDS	Report Findings & Data Sets
IEI	Implement, Evaluate, & Improve

3.4.1 Process Characterization and Modeling Methods

Of all methods reviewed, process characterization (PC) was generally utilized as a method or set of steps in accomplishing the other assessment approaches, for this reason, it is presented first. Five process characterization methods were identified. A generic method is presented by NIST/SEMATECH in their e-Handbook of Statistical Methods [197]; and it includes 1) defining goals, 2) modeling, 3) obtaining results, and 4) reporting. This method is broadly applicable to processes and allows for analysis of any approach, and is not specific to sustainability analysis, and is meant for decision support. Sutherland and Gunter [193] presented a straightforward three-step method to describe manufacturing processes using input-output representations and characterize waste streams and energy consumption. The first and second steps are conduct an inventory and quantify flow rates; the final step is model development, where the inputs are related to the outputs using mathematical modeling. This approach is representative of a characterization method, where the goal is mathematical description of manufacturing processes.

The method proposed by Ibanez-Fores, Bovea, and Belis [67] is used to assess and select best available technologies from a sustainability perspective. While the authors did not explicitly identify the method as a process characterization and modeling method, it was included in this review because it presents similar steps. While being a literature review paper, the authors generated a seven step method: 1) criteria selection, 2) information and data gathering, 3-5) conducting an assessment, and 6-7) finally comparing the options and performing a sensitivity analysis. Cimino-Hurt and Haapala [204] proposed a method for sustainable assessment of new manufacturing processes. The method uses a representative product (i.e. a product that captures the processes under study) as the functional unit, defines a process chain, process modeling, and finally criteria selection for that product. This method is unique, in that the evaluation criteria selection step occurs last, whereas this is the second step in the method presented herein.

The three-step process characterization method described by Mani et al. [20] is used to develop information models of unit manufacturing processes, as well as to help businesses transition into scientific modeling, decision making, and production. The method results in manufacturing process data sets and information models to support sustainability efforts. The information models are represented with SIMA modeling structure. A four step process characterization method is also presented by Mani et al. [20], and is a logical model used for implementation and use of information models. The logical model provides decision support for determining process alternatives. Following process modeling is the execution of the model and generating an inventory for that process, called unit process life cycle inventory (UPLCI), these methods are presented next.

3.4.2 Unit Process Life Cycle Inventory Methods

A UPLCI is a generalized data set for a unit process that contains information pertaining to the transformation of a product by that unit process, and is used for analysis and comparison of processes and products [36]. The data sets generally contain mass loss, energy consumption, and other information. Gonzalez, Kim, and Overcash [31] presented a methodology for generating life cycle inventories for gate-to-gate chemical processes using a unit process approach. This method, a precursor to the more recent methods for conventional manufacturing processes, has four steps: process selection, process definition, mass balance, and energy balance. This method is unique to the later methods in that data collection occurs before the modeling steps. The method developed by Overcash, Twomey, and Kalla [99] is used to generate unit process life cycle inventories (UPLCIs). The method builds off the work of Gonzalez, Kim, and Overcash [31] and is presented later by Overcash and Twomey [36], it is used to generate a UPLCI database [205]. The method, although five steps long, is comprised of planning, criteria selection, and modeling activities. This method is unique as it is the only one to explicitly identify a literature review as a step.

The CO2PE! Initiative utilizes a method described by Kellens et al. [34], [35] to generate UPLCI data. The method is used for analysis and improvement of unit processes. This method differs from other UPLCI methods in that it identifies two different approaches for generating this data, which are 1) the screening approach, and 2) the in-depth approach. These are identified by 2a and 2b in Table 3.1. A database is being generated under the CO2PE! Initiative in an international effort to create UPLCI data for many manufacturing processes [206]. As an extension of the CO2PE! method, Kellens (CH4) [73] proposed a framework for developing parametric environmental process models. The method similarly analyzes process time and resource use of a manufacturing process, and makes use of the prior UPLCI method. This framework is composed completely of data collection and modeling steps. Each of the methods presented below (product assessment, process improvement, and process planning) can utilize either process characterization models or UPLCI data. First product assessment methods are discussed.

3.4.3 Product Assessment Methods

Product assessment methods are used for analyzing products, usually during the design stage, and can be used to compare different products or product features from a sustainability perspective. The method presented by Hula et al. [195] demonstrates a method for design for end-of-life (EOL) product assessment. The first two steps of this method are challenging to incorporate into the unified methodology presented later. The first step involves defining situation variables and EOL scenarios, acting as a background information collection step, is classified as a planning step (Table 3.1). The second step involves both product selection and process mapping, and has been organized into the Identify Process Plan (IPP) step (Table 3.1).

Life cycle assessment (LCA) is a product assessment method [97] presented by ISO 14040 [81] which can be applied to manufacturing processes and systems. It is the inspiration for most other sustainability assessment methods and is recorded here for comparison. Four iterative steps make up this method; steps are revisited as more knowledge is gained throughout the LCA process. Ostaeyen et al. [202] developed a method for economic assessment for product-service systems (PSS), which analyzes a product throughout its lifecycle. This method notably considers the services that are required during the product use phase. The method seeks to identify improvements for a product by identifying and evaluating the services a business can potentially provide from an economic perspective.

Eastlick and Haapala [80] presented a method for comparing product alternatives by analyzing the sustainability tradeoffs incurred by use of different manufacturing processes. The six step method analyzes alternative designs by generating a detailed gate-to-gate assessment. The process models developed for the assessment can be used for future assessments. This method employees a sensitivity analysis to determine the relative influence of each metric on the overall performance. The method presented by Eastwood et al. [33] extended this work. The method presented is used for assessing singular components, but aims at providing more depth. Design alternatives can be compared to assist design for manufacturing decision making. The method clarified that defining the assessment goal and scope is a primary step occurring before generating design alternatives. This is important since the goal of a study is not always to compare design alternatives. Also, the method added identifying key unit processes and constructing mathematical models. Common engineering practice dictates that after developing a product, a process plan is developed for manufacturing it, and process planning is presented next.

3.4.4 Process Planning

These methods are used as an aid in the development and comparison of process plans. Hendriks et al. [192] developed a method using material flow analysis (MFA) to determine the anthropogenic metabolism of a manufacturing process plan. The method consists of five steps: the first two are in the planning category, followed by data acquisition, material balancing and modeling, and, finally, interpretation. The method is similar to that in the more recent text of Brunner and Rechberger [207]. In their book, Brunner and Rechberger [207] provide more detail and a more resources for performing a MFA; in addition they provide fourteen (14) case studies that range in different applications for MFA. Rodriguez et al. [196] proposed a method to identify the improvable flows using material and energy flow analysis (MEFA), which is inspired from the concept of industrial metabolism. This is a four step method, which combines process planning and data collection into the first step, along with modeling and assessment into the second step. The third step is interpretation of findings to select improvable flows. And the last step, best available technologies (BAT) analysis, was drawn from Barros et al. [208], is included as a report findings step. The BAT method repeats some of the analysis previously done and reports out the BAT selection. The method presented by Herva et al. [200] is used to assess the environmental impact of a process plan or manufacturing facility, depending on scope of study. The method is composed of four steps: 1) identify the process plan, 2) energy and material flow analysis (EMFA), 3) ecological footprint (EF), and 4) sensitivity analysis. The final stage of the method uses sensitivity analysis to evaluate changes in the EF via Monte Carlo simulation by applying triangular distributions to the variables in question.

Jiang et al. [201] developed an environmental assessment method for process plans using an assessment matrix with the AHP. The method is composed of three steps. First, collecting inventory data, second, assessing the impacts, and third, analyzing the results for improvement opportunities. The authors noted that other process modeling efforts could be incorporated for evaluation of process plans. Zhao et al. [92] presented a method for environmental process planning that can make use of sustainable manufacturing process characterization methods. The method is iterative in its use of steps: an initial plan is develop, assessed, and reported, and then alternative plans are developed, assessed and reported. This method is unique in that it details the analytical steps required for assessing process plans and identifies areas for improvement via Pareto analysis.

3.4.5 Continuous Improvement

Process improvement and continuous improvement methods focus on identifying the most impactful processes. Many of these methods would make use of either process characterization or UPLCI methods for ranking the processes under question. All of the methods within this section conclude with a continuous improvement step. Pun et al. [194] proposed a method for evaluating the environmental impacts of manufacturing processes. The authors claimed there is no universal method for assessing all manufacturing processes. The first four steps of their method can be described as organizing a team and developing a plan. While this method is described as a process assessment method, the end result is continuous improvement by documenting findings and iterating the method. Jiang et al. [198] develop a method that employs both multi-criteria decision-making and neural network techniques. The method consists of three steps, the first step is a combination of criteria selection and data collection. The second and third steps are both assessment and evaluation steps, the second being an AHP evaluation and the third being neural network evaluation; both can be used to identify process improvements.

Thiede, Bogdanski, and Herrmann [199] developed a process improvement method, which focuses on energy reduction of the most impactful of machine tools. This method starts at the assessment phase, as the first step requires a list of the highest energy consuming machine tools identified following the Pareto 80-20 rule [199]. The final step is modeling and simulation that enables more sophisticated continuous improvement, which, as seen in Table 3.1 is interestingly not last. Dorr, Wahren, and Bauernhasl [203] proposed a method for process improvement for machine tools via energy monitoring. Interesting differences between other methods is that the first step is writing instructions for data generation and measurement, which can be considered a planning activity; and the final step integrates “know-how” for continuous improvement, implying that the method either requires continuous improvement activities or is used to initiate such activities.

3.5 Sustainability Assessment Methodology

Based on the review of the foregoing approaches, a unified sustainability assessment methodology was developed. The main deviations from the previous methods were joining multiple steps into a single step or separating a single step into multiple steps. The order and selection of steps in the previous methodologies makes each unique and relevant for the correct application. The unified method here attempts to provide a generalized approach with roader applicability across processes, industry types, and for varying sustainability objectives. The only drawback to all methodologies, including the one developed here, is the failure to incorporate additional needed steps which are either unforeseen or the authors assumed to be performed regardless.

Figure 3.1 displays the methodology including the framework for modeling and characterizing manufacturing processes, and the subsequent use of these methods. The methodology follows nine steps that are mostly interchangeable, as demonstrated by the review above. The framework organizes the nine steps into three overarching phases. Steps within each phase are generally interchangeable, being done in the order is most fitting for the goals of the assessment. This methodology is designed to be iterative. This implies that practitioners of the method would adopt it into their regular job functions, as with each iteration the practitioner improves the manufacturing facility incrementally. The methodology is also not only limited to the large scale, since as a project continues information increases, and the decisions made from the methods should reflect this new information. This section will outline the activities for each step in each phase (i.e., preparation, execution, and decision).

3.5.1 Preparation

The first phase, the Preparation Phase, involves developing a project plan, selecting evaluation criteria, and identifying a process plan for evaluation. Several methods group these steps into one, and several others assume that these activities are already completed prior to the investigation. When a series of references is listed following an activity, this indicates that those methods contained the activity.

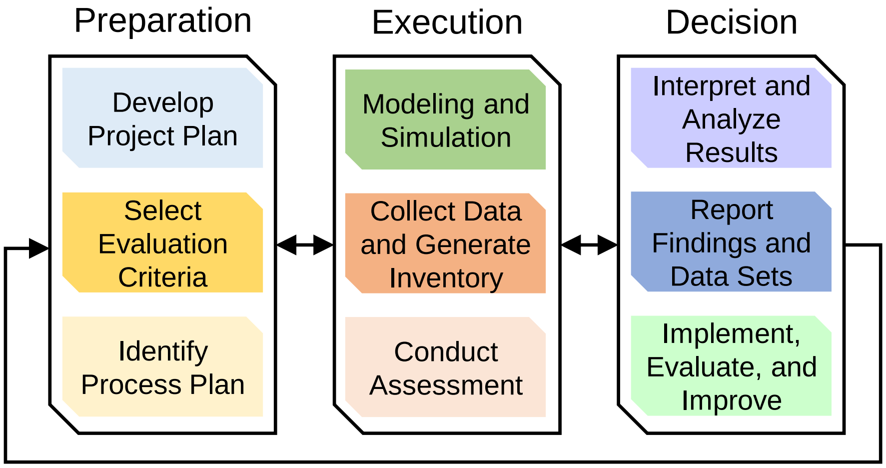


Figure 3.1: Methodology for sustainability assessment of manufacturing processes

3.5.1.1 Develop Project Plan

The first step, developing a project plan, is involves several activities. First, a team should be identified and resources available to the team [194]. A goal statement should be defined for the project [33]–[35], [81], [197], [202]. Background information must be collected from literature and other sources [99], [194], [195]. The functional unit and general system boundaries are identified [34], [35], [81], [202]. In product assessments, the functional unit would be the product evaluated [33], [81] or alternative designs for a single product would be compared [80]. Finally, a write up is prepared outlining each activity identified in this section, along with a description of the remaining steps to be carried out for the project. Several methods included the Select Evaluation Criteria and

Identify Process Plan activities within the first step. Here, these steps were extracted from the planning phase to emphasize their importance.

3.5.1.2 Select Evaluation Criteria

Selecting evaluation criteria requires several considerations. First, to determine the order of removal of the decisions from the origin of the data, i.e. process level vs system level decisions and process vs system level data. Veleva and Ellenbecker [78], identified that metrics were used for process level decisions and indicators for system level decisions, and metrics would have to be abstracted to indicators for system level decisions. Second, is to identify sustainability aspects considering in the study. Third, is to select specific evaluation criteria. Fourth, is to identify the relative importance of criteria. This task is challenging as it asks for practitioners to compare and rank social, environmental, and economic evaluations against one another. Some authors have used the AHP and others have used neural networks [198] to determine relative weightings of each criteria. MCDA has been developed as its own research area, Wang et al. [209] and Ho et al. [210] have thoroughly reviewed the literature and present many criteria selection and weighting methods. Prior work refers to the evaluation criteria as criteria [67], indicators [20], [194], [203], metrics [20], [33], [80], performance measures [198], [203], and parameters [99], [204]. Several authors have identified evaluation criteria at different abstraction levels, i.e., process and system level criteria.

3.5.1.3 Identify Process Plan

The final step in the preparation phase is identifying the process plan. The necessity of this step is dependent upon the type of study the practitioner performs. Process characterization and UPLCI methods would not require this step since only a single process is evaluated, whereas product assessments and process planning would require identification of a process plan. Finally, continuous improvement methods require this step if the method is at a manufacturing line or system level. In some reported methods, the analyst holds responsibility for identification of the necessity a process plan [33], [204], while others detail the approach as data collection and sorting the processes [31], making it recursive with the execution phase. Zhao et al. [92] revisit this step three times throughout their process plan improvement methodology. Others, e.g. Thiede et al. [199], combined the process identification and data collection phases emphasizing the data required. Others assumed that the process plan was already identified, e.g. [201]. Finally, many organize this step into the Develop Project Plan step as part of defining the system boundaries [34], [35], [81], [202].

In sum, the Preparation Phase of the method generally follows this flow, but, depending on whom initiates the study, these steps may be reorganized. Upper management may identify a specific product or manufacturing line to investigate. In addition, it is suggested to include the evaluation criteria and process plan in the written plan developed in the first step of the phase, to be executed in the Execution Phase.

3.5.2 Execution

The Execution Phase includes the following steps: Modeling and Simulation, Data Collection and Generate Inventory, and Conduct Assessment. Here, the modeling step involves developing mathematical models for the manufacturing process under question. Collection of data and generating an inventory involves obtaining data for use in another step, usually for conducting an assessment. Finally, the Conduct Assessment Step is when the practitioner creates results, usually using the models and data from the previous two steps.

3.5.2.1 Modeling and Simulation

Modeling and Simulation is developing mathematical models for each process to instantiate the evaluation criteria as identified during the Preparation Phase. While most authors did not state this as an explicit activity, models are developed often for application in such studies; the following studies identified different modeling methods to use. In process characterization, these studies identified input-output modeling, process interaction modeling, information modeling, and energy modeling. Sutherland and Gunter [193] identified input-output modeling for use in process characterization. Cimino-Hurt and Haapala [204] noted that the modeling phase should be reflective of the sub-process interactions. Information models developed by Mani et al [20] are used as a framework for structuring the information characterizing processes. UPLCI efforts specify input-output models for mass and energy flows [31], [34], [35], [99]. Gonzales et al. [31] identified five specific energy calculations for chemical processes. For product assessment, Hula et al. [195] suggested that both economic and environmental models are needed for decisions and that a multi-objective optimization problem should be constructed using the models. Eastwood et al. [33] developed mathematical models to quantify evaluation criteria for each of the three sustainability domains. Ostaeyen et al. [202] noted that economic models were needed in process planning. In continuous improvement, Thiede et al. [199] specified that simulations should be developed from input-output modeling efforts.

3.5.2.2 Collect Data and Generate Inventory

This step of the Execution Phase involves rigorous on-the-floor observation and data collection [67], [194], [197], [199], [202], [203]. Data can also be collected from literature, handbooks, and other documentation [20]. This step is also called collecting a process inventory [34], [35], [81], [193], [201]. Jimenez-Gonzales et al. [31] referred to this step as defining the process, and identified five specific data requirements for chemical processes; these include 1) heat of reaction and heat of dilution, 2) sensible heat to reach reaction conditions, 3) energy for separation units, 4) energy for transportation of materials, and 5) potential energy recovery. Finally, several authors identify this as a model validation step, but this may require some cycling back to the modeling step by developing regression models from the data collected [34], [35], [202]. All information needed is collected during this step, but not all information is known that is needed at this stage, thus revisiting this step is suggested. General observations are usually required for the modeling step, and hard data is required for the assessment step. This makes the modeling and data collection steps cyclical, but the assessment step usually comes after these two steps.

3.5.2.3 Conduct Assessment

The conduct assessment step consists of carrying out the plan to generate results in the form of the evaluation criteria. Here, the collected data is used with the models created to generate results useable during the Decision Phase. Under ISO 14040 [81] this step is labeled as assessment, while other authors have defined this step as quantifying indicators [33], [92], [201]. And Ibanez-Fores et al. [67] further clarified this step as obtaining, normalizing, and weighting indicators. Other authors have described this step as quantifying the mass and energy flow rates [193], calculation of optimal trade-offs [195] or evaluation of alternatives [80], and setting baselines for improvement [198]. Some incorrectly labeled this as a field and laboratory analysis [194], which actually takes place after results are calculated.

With the assessment conducted, some may feel the need to reevaluate alternatives before reporting the findings, thus it is suggested to visit the decision phase and catalogue the initial findings before moving on. Rushing to rectify poor results can cause an overzealous engineer to omit documenting the knowledge gained from said poor results. With the results calculated, the methodology transitions into the decision phase, where results interpretation, reporting and databasing, and continuous improvement efforts take place.

3.5.3 Decision

The decision phase is composed of three steps. Interpret and Analyze Results is any additional preparation of the results beyond quantifying them. The next step, Report Findings and Data Sets, is reporting and saving the results for decision making and later use. Finally, in Implement, Evaluate and Improve, the organization incorporates the herein methodology as part of its regular operations.

3.5.3.1 Interpret and Analyze Results

Here, the practitioner will develop the results beyond the evaluation criteria identified during the Preparation Phase. This analysis should improve information understanding and comprehension, identified analysis methods include graphical, sensitivity, alternatives and design comparisons. The following analysis methods were identified in the respective sources. Several authors left the identification of analysis techniques up to the practitioner [81], [194], [203]. Quantitative and graphical analysis are developed [195], [197]. Sensitivity analysis is performed [67], [80], [200]. Options and alternatives, machines or designs, are compared against one another [33], [67], [80], [92]. Finally, improvement opportunities are identified [92], [201].

3.5.3.2 Report Findings and Data Sets

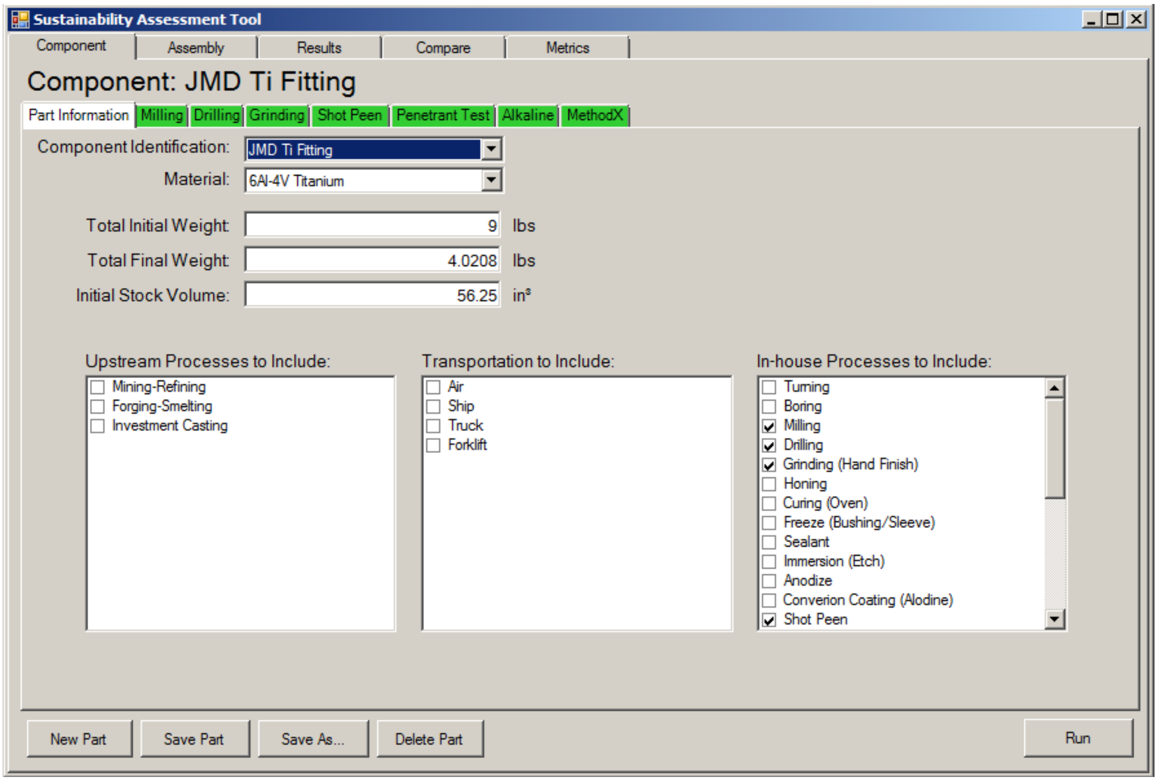
In the Report Findings and Data Sets step, the practitioner communicates the study outcome and descriptively catalogues and stores the models, data, results, and analysis for future use. Several authors included a report step [194], [197], and others included a data storage step [20], [34], [35], [194]. A catalogue or database could be generated with the information models described by Mani et al. [20]. Generating a descriptive database early and adding to it as the study progresses will benefit a proactive analyst to minimize potential lost or unorganized data, thus save the practitioner much headache in a long study. More effort put into storing the data for future use will enable more rapid implementation of continuous improvement.

3.5.3.3 Implement, Evaluate and Improve

The practitioner implements changes and improvements identified in the Report Findings and Data Sets Step, and then evaluates and validates the improvements made. Several studies, Thiede et al. [199] and Dorr et al. [203], called for continuous improvement to be implemented as the last step in their methods. Other authors [194], [198], [202] suggested that improvement should occur. A continuous improvement cycle is a method that identifies improvements, implements one or more, and then restarts. In this last step, the analyst is asked to evaluate and validate the improvements made, and is another Execution Phase with a predefined Preparation Phase. Thus the practitioners are initiating continuous improvement. Initiating continuous improvement in an organization can be a challenge, but can be facilitated through identification of commonly beneficial initiatives.

3.6 Demonstration of the Methodology

This section will provide a demonstration for the unified methodology presented above. Specifically, a design for manufacturing decision support software was developed via mathematical unit manufacturing process models. The software tool (Figure 3.2) was described and demonstrated by Garretson [112]. The methodology will be described step-by-step in developing an assessment of an example aircraft-like assembly. The assembly is composed of several different metal materials to demonstrate the range of the method for assessing different unit manufacturing processes (UMP). This section will walk through the three main phases of the methodology and then describe the development of the software tool to realize the approach. Because the models implemented into the tool are generalized, the tool does not have to be tailored for every assessment; it will need to be updated to incorporate process models not included previously.



Component: JMD Ti Fitting

Component Identification: JMD Ti Fitting
Material: 6Al-4V Titanium
Total Initial Weight: 9 lbs
Total Final Weight: 4.0208 lbs
Initial Stock Volume: 56.25 in³

Upstream Processes to Include:
- ☐ Mining-Refining
- ☐ Forging-Smelting
- ☐ Investment Casting

Transportation to Include:
- ☐ Air
- ☐ Ship
- ☐ Truck
- ☐ Forklift

In-house Processes to Include:
- ☐ Turning
- ☐ Boring
- ☑ Milling
- ☑ Drilling
- ☑ Grinding (Hand Finish)
- ☐ Honing
- ☐ Curing (Oven)
- ☐ Freeze (Bushing/Sleeve)
- ☐ Sealant
- ☐ Immersion (Etch)
- ☐ Anodize
- ☐ Converion Coating (Alodine)
- ☑ Shot Peen

Figure 3.2: Software tool interface used to realize the sustainability assessment methodology

3.6.1 Preparation

Improvement to manufacturing systems can be accomplished using many different strategies. This demonstration aims to improve manufacturing performance from the perspective of a particular manufactured product. Analysis of a product provides multiple benefits. First, UMP improvements for that specific product can be identified; second, candidate features can be identified; and third, a report of product sustainability performance can be produced. While the analysis of this assembly will identify improvement areas for its specific components, the method can be applied to a broader range of manufactured components to highlight improvement opportunities. The manufacturing process flow presented in this example is one approach for crafting the product, and it is unknown if this is the best method.

The first phase of the assessment, preparation, involves developing a plan, selecting evaluation criteria, and identifying a process plan for evaluation. Thus, this phase of the assessment defines the goal and the scope for the study.

3.6.1.1 Develop Project Plan

The project plan developed for the research is outlined below in a bullet point format. A plan would be written up for this assessment, the plan includes all the information from the preparation phase. The plan continues in Table 3.2 and Figure 3.3 below.

1. <u>Team</u>: researchers from Oregon State University and engineers from Boeing Portland.
2. <u>Resources available to the team</u>: component specifications created by the team, manufacturing process parameters adapted from Boeing practices, and academic literature.
3. <u>Goal</u>: to generate a gate-to-gate manufacturing sustainability analysis for an example aircraft like assembly.
4. <u>Reasoning</u>: An analysis would enable engineers to improve the sustainability performance of the assembly, and more specifically, spotlight specific areas for improvement. To direct the search for improvement areas, the components in each assembly are compared against one another. To generate improvements, alternative designs are generated for the example assembly.
5. <u>Functional Unit</u>: The functional unit for the assessment is one assembly, seen in Figure 3.3.
6. <u>Description of Product</u>: The assembly is made up of 4 components: Parts 1 and 2 are steel, Part 3 is stainless steel, and Part 4 is titanium. Two of Part 1, one of Parts 2-4, and 30 fasteners are included in the assembly.
7. <u>Assumptions</u>: The fastener manufacturing processes occur upstream and are not included in the sustainability assessment.

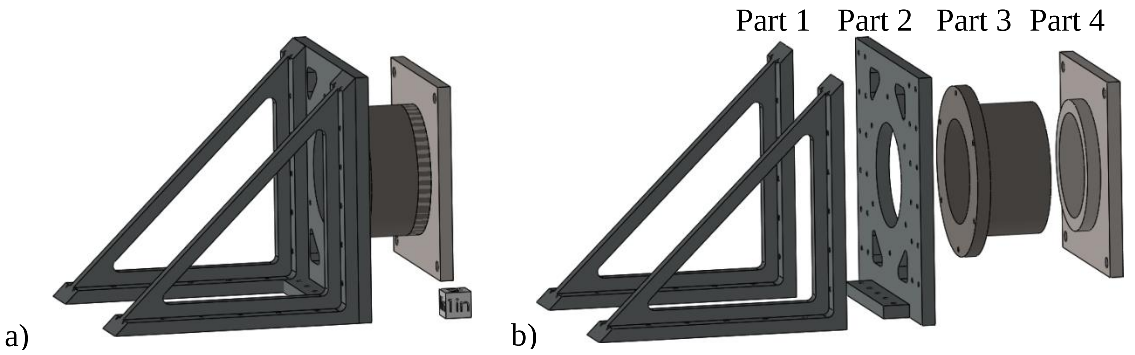


Figure 3.3: Example aircraft-like assembly, a) assembled view, b) exploded view (1 inch block included for reference)

3.6.1.2 Select Evaluation Criteria

When selecting evaluation criteria, the main need is identifying the specific decisions that will be made using the assessment. The process involves asking several questions. Who will use the results and analysis to make the decision? What process knowledge the person have? What level of detail is required for their decision? Is their decision a process level, system level, or corporate level? In this demonstration results and analysis would be used by design and manufacturing engineers to make design for manufacturing decisions, i.e. process and system level decisions. The manufacturing system is impacted by the decision, and would result in redesign or improvement of a component or process. Process specific metrics have been selected for this assessment (Table 3.2). More abstracted indicator values may not help engineers identify the best area for improvement.

3.6.1.3 Identify Process Plan

The scope for the sustainability assessment is crucial to develop meaningful and communicable results. When process plans are not appropriate, the step can be substituted for an in-depth scope definition. The process plan developed here identifies each processing step that each component undergoes.

Table 3.2: Selected criteria for sustainability assessment

Domain	**Indicator**	**Metric**	**Unit**
Economic	Economic	Operating Cost	$
	Market Presence	Cost from US Suppliers	%
Environmental	Materials	Input Material Non-Flyaway Content	%
		Input Material Virgin Content	%
	Energy	Off-site Energy Consumption	kWh
		On-site Energy Consumption	kWh
	Water Consumption	Water Use	L
		Water Discharge	L
	Emissions	GHG Emissions	kg CO$^{2\text{ eq}}$
		ODS Emissions	kg CFC$^{-11\text{ eq}}$
		Pollutant Emissions	kg
	Waste	Waste to Landfill	kg
		Waste to Incinerator	kg
		Waste to Recycle	kg
		Hazardous Waste	kg
Social	Employment	Average Wage	$/hr
	Operational Health and Safety	Acute Injuries	injuries
		Lost Work Days	days
		Chronic Illnesses	illnesses

The process plans can be identified from an operations sheet, value stream map, or manufacturing process flow. Processes with little to no impact can be omitted from the assessment, and the processes identified with discretion of the assessor. These judgments are based on processing knowledge and probable relative impact on the evaluation criteria. The omitted processes from this assessment are inspection tasks and marking tasks. The process plan is now incorporated into the written plan defined in the planning step. The process plans can be seen in Figure 3.4. With the preparation phase complete, the assessment moves on to the execution phase.

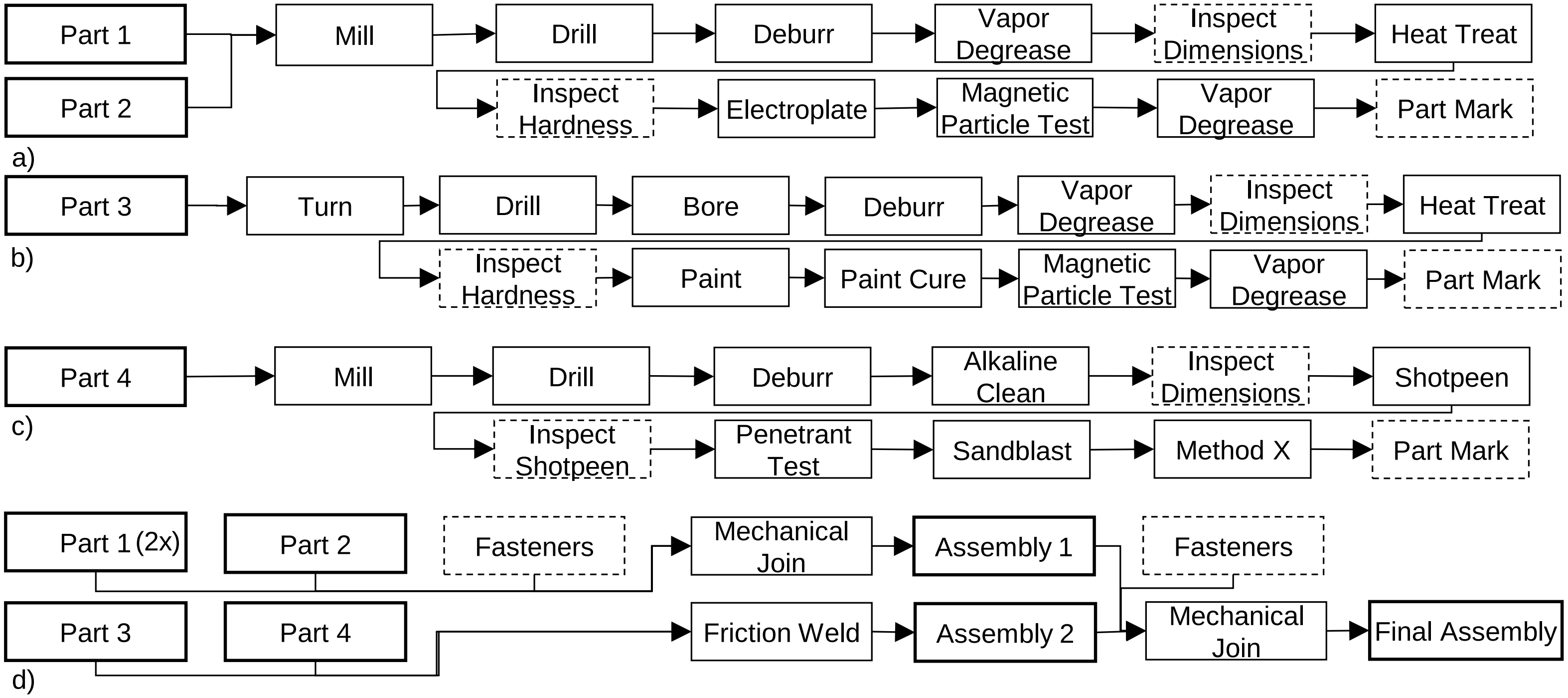


Figure 3.4: Process plans for component manufacturing and assembly: a) Parts 1 and 2 are steel, b) Part 3 is stainless steel, c) Part 4 is titanium, and d) is an assembly of components. Dashed processes are not included in assessment.

3.6.2 Execution

The Execution Phase in this study was performed cyclically for each part and the assembly to create the assessment seen in Section 3.6.2.3. For each part this phase follows the same format of modeling, collect data, and conduct assessment. The aggregated assessment is reported in Section 3.6.2.3, and further analysis is carried out in the Decision Phase below.

3.6.2.1 Modeling and Simulation

For the assessment, mathematical representations are created for each UMP for each evaluation criterion. Intermediate calculations are performed to capture sub-process interactions, e.g. motor horsepower. While these models are stored and used in a Microsoft (MS) Excel workbook, the methodology could be realized with other software. UMP models are generated much like input-output models for UPLCI applications, but input-output models are limited to mass and energy, which can be used to quantify some of the metrics identified in the prior phase. With additional effort, models can be implemented in simulation software. The software generated for this study did not implement Monte Carlo simulation, but did allow for investigations of alternatives.

3.6.2.2 Collect Data and Generate Inventory

Data collection is carried out with the help of manufacturing engineering experts. Working with the manufacturer, this requires on-site investigations and interviews. Where data was not available on the shop floor, or collection equipment was not at hand, academic literature, handbooks, and machine documentation is utilized. The data was stored within several MS Excel workbooks, one for each component, but other data storage software can be utilized. This step will influence the modeling step and requires iterations between the two steps, since the models made are dependent upon the available information. Regression models, for example, can be made using data collected as a means for validating theoretical models.

3.6.2.3 Conduct Assessment

After gathering all necessary data, models and data are aggregated creating results available for analysis and decision support. The numerical results for the assessment of the example assembly are displayed in Table 3.3.

3.6.3 Decision

With modeling completed and results generated, analysis, reporting, and improvement steps are undertaken. The Decision Phase is less cyclical than other phases, but initiates the methodology to start again in a continuous improvement cycle. The parts of the example assembly are compared here to identify the most substantiated areas of improvement, i.e., to focus improvement efforts on parts and evaluation criteria that have the most potential for change.

Table 3.3: Assessment results for the example aircraft-like assembly

Metric	**Unit**	**Total**
Operating Cost	$	751.03
Cost from US Suppliers	%	-
Input Material Non-Flyaway Content	%	50.96
Input Material Virgin Content	%	-
Off-site Energy Consumption	kWh	-
On-site Energy Consumption	kWh	3102.78
Water Use	L	53.35
Water Discharge	L	13.39
GHG Emissions	kg $CO_{2\ eq}$	473.52
ODS Emissions	kg $CFC_{-11\ eq}$	-
Pollutant Emissions	kg	4.16
Waste to Landfill	kg	11.90
Waste to Incinerator	kg	-
Waste to Recycle	kg	30.45
Hazardous Waste	kg	0.04
Average Wage	$/hr	20.19
Acute Injuries	injuries	5.36E-04
Lost Work Days	days	6.46E-03
Chronic Illnesses	illnesses	3.26E-05
Process Time	hrs	21.76

3.6.3.1 Interpret and Analyze Results

Analysis is performed to identify the most impactful processes for the assembly. Here, graphical analysis is presented. Because meaningful data visualization can be a challenge, similar data are presented in the figures. Figure 3.5 is a comparison of the component level impacts of the assembly. The figures are normalized comparisons, where the results for each part are divided by those of Part 3. This causes values for Part 3 in Figure 3.5 to be equal to one, and values for Parts 1,2 and 4 are referenced against Part 3. Part 3 was selected for normalization because it had the most smallest values Figures below identify ratio values, ratio values correspond to the normalized result values.

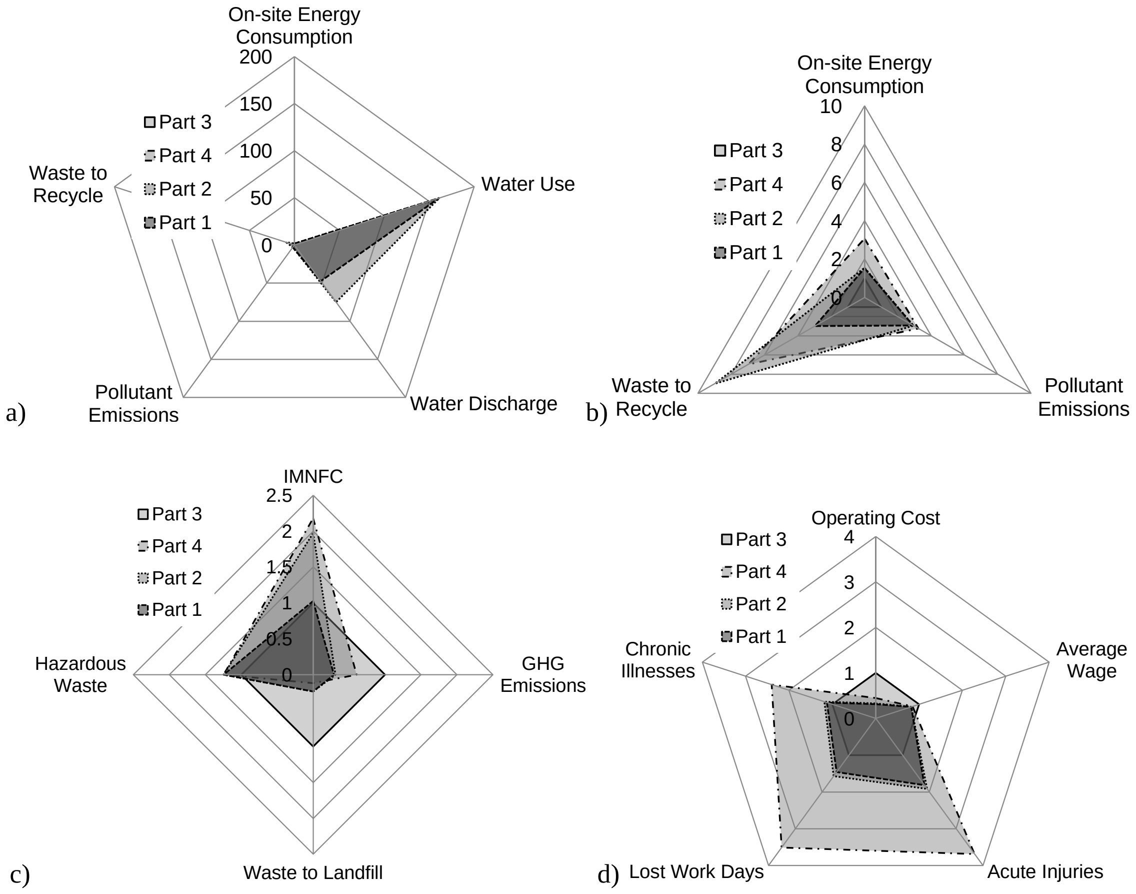


Figure 3.5: Comparison of non-zero evaluation criteria. a-c) environmental criteria with a) ratio >3, b) ratio >3 without water, and c) ratio <3, and d) non-zero economic and social criteria.

The downside to this approach is that large values of the reference part (Part 3) appear small because they are set to one, e.g. Figures 3.5c show that greenhouse gas (GHG) emissions and waste to landfill are dominated by part 3. Alternative normalization and comparison schemes can be used for evaluating components. These include normalizing by initial stock volume, final part volume, by surface area, by mass, or another component property. These alternatives identify non-discrete impact, whereas normalization by part identifies discrete impact. Figure 3.5 provides comparisons for each sustainability aspect.

Parts 1 and 2 are made from steel, and a functional requirement is non-corrosivity, thus necessitating electroplating, which results in a large consumption of water. Since the relative impact of water consumption for these two parts is so high, the water-related criteria are removed in Figure 3.5b. Part 4 has significantly higher values for on-site energy consumption, pollutant emissions, acute injuries, and lost work days (Fig. 3.5b). Finally, the values for part 3 are seen to be miniscule relative to other components in Figures 3.5 a and b, this is inherent in the approach because ratio values large relative to part 3 were chosen.

Parts 2 and 4 have the largest amount of material removed from their initial stock volume at 108.98 in^3 and 31.12 in^3 respectively; thus, they contribute the greatest to waste to recycle and input material non-flyaway content (Fig. 3.5b and c). Part 3 being stainless steel is the only one that requires painting, thus it has the highest waste to landfill as a result of waste materials from the painting process (Fig 3.5c).

Machining of titanium requires much more time and energy than softer metals, the machines run at slower speeds and feeds to utilize higher torque. Thus part 4 requires longer processing times on operator based processes than other parts and results in the greatest contribution to operator based social criteria, being acute injuries, lost work days, and chronic illnesses (Fig 3.5d). Finally Part 3 requires the most processes to produce, and has more time spent at more knowledge based processes thus resulting in the largest operating cost and largest average wage (Fig 3.5d).

Note that while the figures provide reference for improvement direction and focus for the specific parts or specific evaluation criteria, the graphical analysis does not provide reference for preference of one criteria over the other. Criteria preference evaluation would be completed based on the judgement of the decision maker. Also, sensitivity analysis could be performed to identify which criteria are most effected by design process changes. Such an analysis can aid in defining an improvement direction, but the analysis does not indicate relative importance of individual metrics.

3.6.3.2 Report Findings and Data Sets

A report, such as this article, is prepared to document the study and its findings. The results are stored in a database for later use. The information stored includes the data and UMP models generated to assess the example parts. Reference back to the report and models will enable speedier continuous improvement efforts in the future.

3.6.3.3 Implement, Evaluate and Improve

Improvement efforts are continued by either systematically targeting the subsequently most impactful materials, components or processes for the given product, or by applying this methodology to alternative assemblies, designs, processes, or process plans. Storing the results in a database provides a means to continuous improvement as well, stored data is not valuable, however, unless another application is carried out using that data.

Figures 3.6 and 3.7 provide an example of further analysis for continuous improvement efforts. Figure 3.5 provided focus for improvement efforts for specific component and criteria intersections. Now investigation into specific component, criteria, and process intersections allows us to identify the specific UMPs improvements to reduce specific evaluation criteria. After an improvement is made, these graphs can be regenerated with new data to incorporate into a continuous improvement scheme.

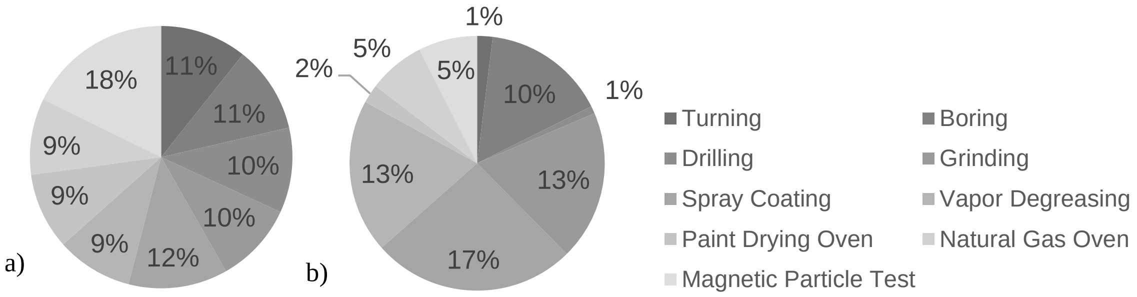


Figure 3.6: Selected component, criteria, and process intersections for Part 3. a) average wage, b) operating cost.

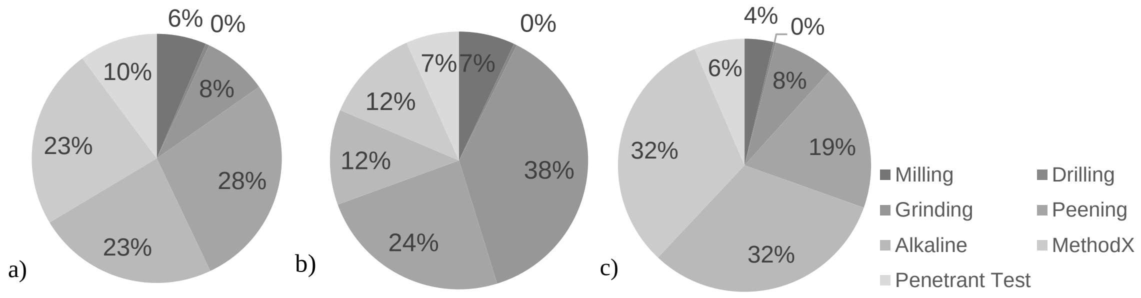


Figure 3.7: Selected component, criteria, and process intersections for part 4. a) acute injuries, b) lost work days, and c) chronic illnesses.

Figure 3.6a shows that the magnetic particle test (18%) has the largest impact to average wage. Paying employees less is usually frowned upon but reducing processing time would decrease this metric. Figure 6b shows that to reduce operating cost for Part 3, spray coating (17%) would be the place to start. Viable options include reducing the amount of overspray, masking tape and paper, and spray time (to reduce operator cost and air compressor run time). Figure 3.7a shows that reduction in acute injuries for Part 4 would occur at peening (28%), alkaline (23%), or method X (23%). Figure 3.7b shows that reduction in lost work days should occur at grinding (28%) and peening (24%).

Finally, reduction in chronic illnesses would occur at alkaline (32%) or method X (32%). Acute injuries, lost work days, and chronic illnesses are calculated from average injury data and processing times, thus reducing exposure to injuries and reducing processing time will yield improvements. After improvements are made to these areas, the example assembly can be reassessed to identify the next areas for improvement.

3.7 Summary and Conclusions

This paper reviewed 23 methodologies that integrate sustainable assessment of manufacturing processes within a methodology for either process characterization, UPLCI, product assessment, process plan assessment, or continuous improvement. Many other papers were investigated, but those without explicit methodologies reported were not reviewed. This area of literature can be broadly defined as systematic improvement of manufacturing processes. Despite the variety of methodologies reviewed, a standardized method is possible. And the review provides reference for those requiring more detail in any particular field. The methodology is a cyclical framework of stepwise phases that can be applied to UMP characterization, UMP improvement, manufacturing system improvement, product assessment, and product improvement. This methodology can be described as a bottom up aggregative approach to sustainability analysis. The nine steps for the methodology are outlined in three phases (A, B, and C): *A. Preparation*: 1. Develop Project Plan, 2. Select Evaluation Criteria, 3. Identify Process Plan. *B. Execution*: 4. Modeling, 5. Collect Data, 6. Assessment. *C. Decision*: 7. Interpret & Analyze, 8. Report Findings, and 9. Initiate Continuous Improvement.

The methodology is designed to be iterative. Each of the phases will require cyclical action with the evolving nature of investigations. Newly identified processes can change the process plan and evaluation criteria, newly discovered data can change the modeling and data collection, new analysis methods can identify different improvement areas. As shown in section 3.6, the methodology can provide improvement direction for component manufacturing. The analysis identified several areas for improvement: 1) reducing the water consumption in steel machining operations for parts 1 and 2, 2) reducing stock size or redesigning component features to reduce recycled waste and input material non-flyaway content for parts 2 and 4, and 3) reducing processing time for the titanium processes to reduce acute injuries, chronic illnesses, and lost work days for part 4. The methodology helps to avoid trial and error improvement strategies. Unlike previous methodologies, the one presented here encompasses the entire improvement chain. Where multiple methods were required to generate manufacturing systems improvements from characterized UMPs, modularity and cyclicality aspects enable the use of the a singular methodology.

Future work includes developing generalized UMP characterization formats for specific unit manufacturing processes. Creating generalized modeling formats will enable standardized sustainability assessments throughout a supply chain; this is important for comparison of manufacturing processes and relying on external data from a design for manufacturing perspective. Reviewing and developing generalized models for unit manufacturing processes would fast track standardized sustainability models. Reviews of modeling approaches for specific manufacturing processes are needed. Reviewing modeling approaches for specific UMPs will enable the development of standardized templates. Further, composable models are needed that are capable of transferring information along a process flow from one to the next or previous. Identifying relative uniqueness of each manufacturing process will enable composable UMP characterization. Finally, developing composable UMP characterization allows for advanced software applications that can predict sustainability performance from product and process features.

3.8 Acknowledgements

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3.9 Disclaimer

Certain products or services are identified in the paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products or services identified are necessarily the best available for the purpose.

CHAPTER FOUR: CHARACTERIZATION OF UNIT MANUFACTURING PROCESSES AND THE WORKPIECE FOR COMPOSABLE ANALYSES

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CHAPTER 4: CHARACTERIZATION OF UNIT MANUFACTURING PROCESSES AND THE WORKPIECE FOR COMPOSABLE ANALYSES

4.1 Abstract

Characterization of unit manufacturing processes (UMPs) at industrial facilities increases manufacturing control for sustainability improvements, e.g., cost reduction, waste reduction, lead time reduction, and labor health improvement. These benefits can all be derived from individual process analysis by evaluating UMP models for desired evaluation criteria. An additional benefit from characterizing UMPs is improvement in process planning and design for manufacturing alternatives evaluation, and is accomplished by composing UMP models. Composing UMP models assumes that the output of a prior UMP is the input of a subsequent UMP, and while this is obvious physically, the workpiece hosts information during the transfer. This assumption forces UMP modelers to identify the routes of information transfer, and can include physical, tangible, real life phenomena; and while networking can also transfer information between UMPs, it is excluded here. The focus herein is on the tangible information transfer mechanism, commonly identified as the workpiece. Historically, the focus has been on geometry based workpiece modeling, e.g., computer aided manufacturing (CAM). Modeling the properties of a workpiece will be the focus herein, including processes altering workpiece properties and workpiece properties influencing process selection and process settings.

4.2 Keywords

Unit manufacturing process modeling, workpiece modeling, composability, sustainable manufacturing, ontology

4.3 Introduction

Unit manufacturing process (UMP) modeling and characterization is performed to relate inputs to outputs and gather any information of a process for future evaluations. UMP modeling and characterization applications include assessment of processes, products, and production plants and decision support for identifying improvement opportunities. A future use of UMP models is multi criteria decision analysis (MCDA) and optimization of manufacturing systems and process systems, which includes process plan development and computer aided process planning (CAPP). Currently, UMPs are modeled as functionally independent objects and assessments are performed by aggregating independent data. To facilitate optimization of manufacturing process flows (MPFs) interaction supporting models are needed. In manufacturing systems, the common interaction between all UMPs is the workpiece. The workpiece is the object that each UMP acts on to transform its geometry or properties. The resulting need is a modeling framework that supports interaction between different UMPs by modeling the action of the UMPs on the workpiece, this action is identified as the transformation.

The modern UMP concept was established by the National Research Council (NRC) [211] as “the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product.” This concept is commonly represented as a box with inputs and outputs entering and leaving it, as seen in Figure 4.1. Figure 4.1a is a UMP representation adapted from the NRC. It separates the information, resources, inputs and outputs, thus providing further categorization of a UMP. Figure 4.1b explicitly identifies the workpiece separately from all other inputs and outputs because the function of a manufacturing process is to modify the workpiece, thus the workpiece is given special treatment. Furthermore, a goal in continuous improvement of processes is to reduce all non-workpiece inputs and outputs of the UMP, thus the representation designates the desired matter (the workpiece) and the undesired matter (all other inputs and outputs). Both conceptual models are useful for identifying the varying array of UMPs and organizing the multitude of information of each.

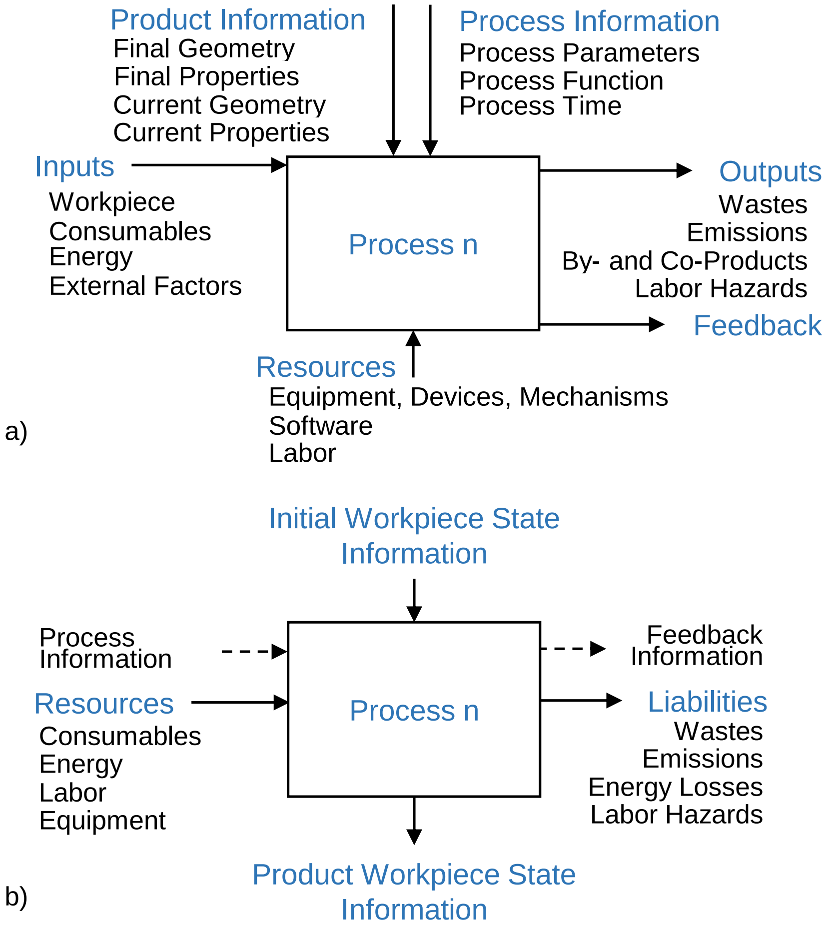


Figure 4.1: Conceptual representations of a unit manufacturing process. a) emphasis on information categories (adapted from [17]), and b) emphasis on workpiece flow (adapted from [17]).

Building on the concept of Figure 4.1, MPFs are developed displaying the subsequent UMPs along with the initial and final product, see Figure 4.2a. Interjecting the workpiece into the MPF results in Figure 4.2b, wherein the workpiece is described between each UMP and identified as the workpiece state. Each subsequent workpiece state incorporates the information of each subsequent UMP.

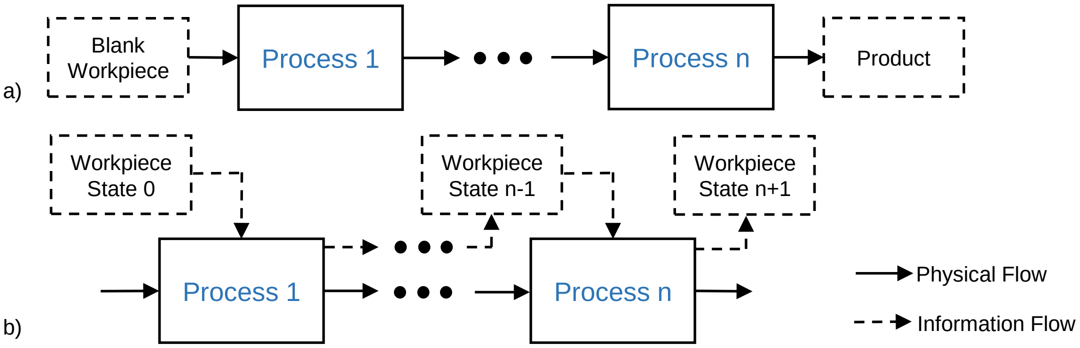


Figure 4.2: A manufacturing process flow. a) showing only processes, and b) identifying the intermediate material states. Material flow is shown as solid lines and information flow is shown as dashed lines.

Note that both Figure 4.2a and 4.2b can be expanded to show an entire supply chain. The basis for this research paper herein is then to model the state of the workpiece. This is similar to the recognized product flow instances in the ontology work by Zhang et al. [212], and Witherell [213], but while the mentioned work uses the representation to designate constituents, this work identifies the underlying information that the workpiece substantiates.

Figure 4.3 demonstrates the concept behind evaluating an MPF using UMP models. Individual models are first evaluated for specific evaluation criteria. These evaluation criteria are aggregated to determine process performance, seen in the light red boxes. Individual process performances are be then aggregated to determine the performance of an MPF or a production plant, seen in the black box and identified as manufacturing system performance. This figure is an informational MFP. Mani et al. [20] have shown that such models can be created using the sima modeling language, and are representable using an IDEF0 modeling software. Furthermore, the figure shows how evaluation criteria are identified and monitored from a bottom up approach. But the framework as shown is limited because individual UMPs are disjointed, integrating the workpiece into the MPF will compose the UMP models.

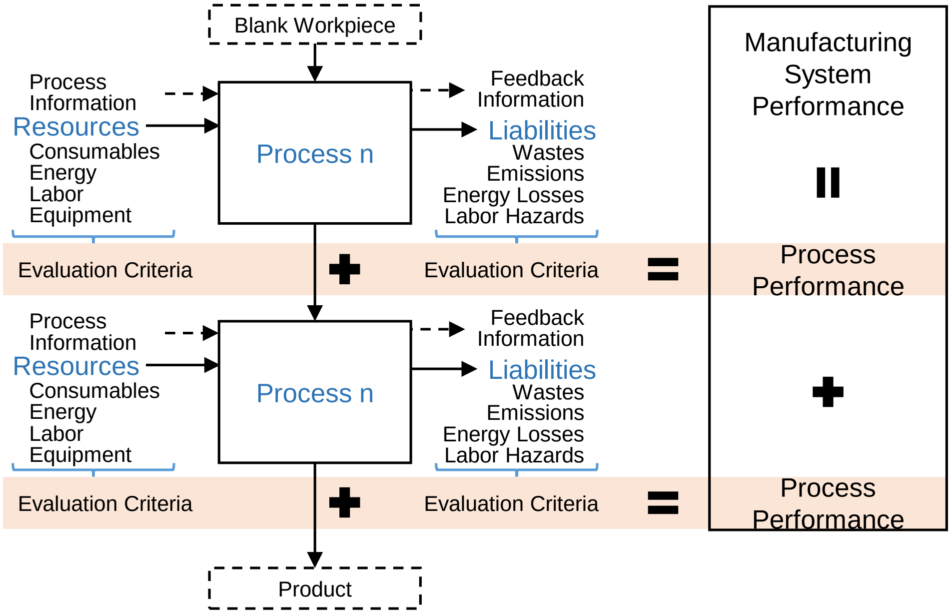


Figure 4.3: Evaluation of an informational manufacturing process flow

Incorporating the workpiece into the informational MPF yields Figure 4.4, which is a workpiece integrated MPF designating the inputs and outputs for each process. This figure shows the concept of transferring information from one process to another, represented by the dashed orange arrows. Specifically, it is showing the process information (process settings) influencing the transformation on the workpiece in process n, and then the workpiece transfers some information to process n+1, which then influences the process n+1 process settings and outputs. Thus the process settings of process n influence those of process n+1, this may be obvious to a process planner, but the previous model (Figure 4.3) does not allow for this interpretation. In sum, what has yet to be organized succinctly are the requirements and results of specific UMPs, and furthermore modeling the workpiece-UMP interaction.

Thus the research problem is that information is not transferred between UMP models, and to transfer information the workpiece state must be described and the workpiece transformation must be modeled. Furthermore, the information transferred by the workpiece can be represented and extracted, and has been in traditional process planning, but possibly has not been integrated into CAPP. Additionally, standardizing measurements for sustainability characterization is needed, as Figures 4.3 and 4.4 do not specify measurements for quantifying predetermined evaluation criteria. In sum the research question is, “What inherent information is in a product and a manufacturing system that can aid in UMP selection, MPF development, and manufacturing system assessment?” Thus the sections of the work herein are Section 4.4 Conceptual Approach, Section 4.5 Application in Mathematical Modeling, and Section 4.6 Conclusion.

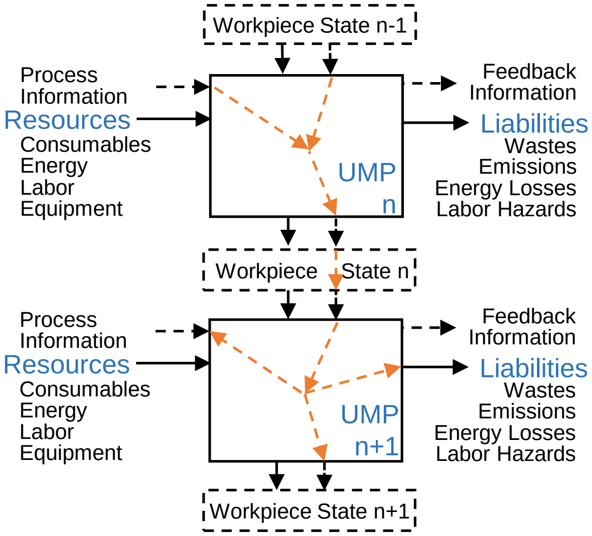


Figure 4.4: Workpiece integrated manufacturing process flow, demonstrating process information of a prior process influencing the next process.

4.4 Conceptual Approach

The objective of this work is to progress UMP characterization by enabling the composition of subsequent UMP models within MPFs. This objective is accomplished herein by identifying the different information that can be either extracted from or provided to a UMP. These information transferring methods are identified as a causal process network and a workpiece-UMP interaction. A causal process network is described in section 4.4.1, and summarized as semantic relationships between UMPs that describe precedence within an MPF. Workpiece-UMP interaction is detailed in sections 4.4.2-4.4.5, a hierarchal overview can be seen in Figure 4.5. Figure 4.5 has five columns and shows the UMP-UMP relations first, the UMP information second, the UMP-workpiece relations third, the workpiece information fourth, and workpiece-workpiece relationships fifth.

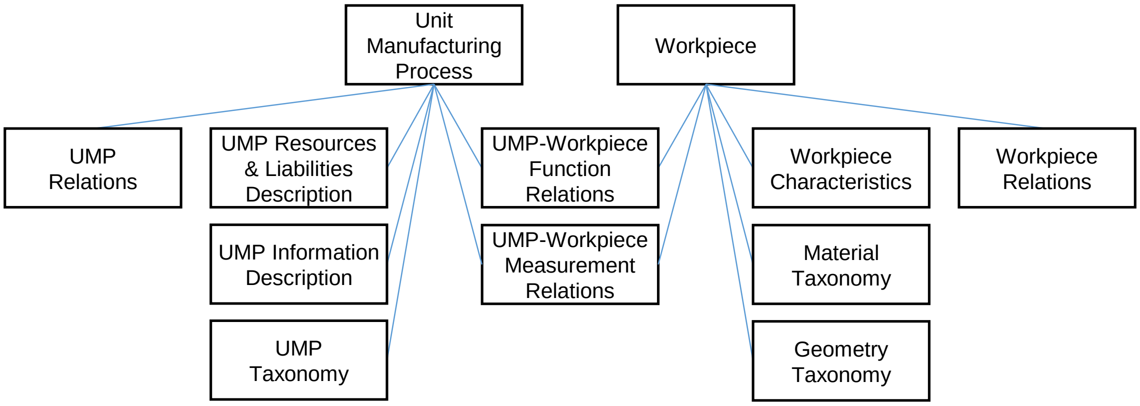


Figure 4.5: Overview of characterization structure

Characterizing descriptions are developed for both the UMP and the workpiece. The UMP description includes resources, liabilities, information, and a taxonomy, while the workpiece description includes characteristics, a material taxonomy, and a geometry taxonomy. Both the UMP and the workpiece will have self-relations. The UMP-UMP relations together form a causal process network, whereas the workpiece-workpiece relationships for an assembly and are designated by joining UMPs. Finally, two relationships exists between a UMP and a workpiece. First is the functional description of how a UMP transforms and adds value to a workpiece, and second is the measurement description used which extracts data from both the UMP and workpiece to quantify evaluation criteria.

4.4.1 Causal Process Network

Requirements and limitations can be derived from UMPs and the workpiece that narrow the choices of immediately preceding (n-1) UMP and immediately following (n+1) UMP of any specific (n) UMP. This idea is defined as the forward method for identifying following UMPs and the backwards method for identifying the preceding UMPs, see Figure 4.6. Furthermore, preceding and following UMPs can be identified as either immediate or non-immediate. Thus each UMP (k) is related to another UMP (n) four times, taking the relationship of required, allowable, or impossible at each. These relations are identified as limitations and requirements because they serve to limit the available options for UMP selection during process planning.

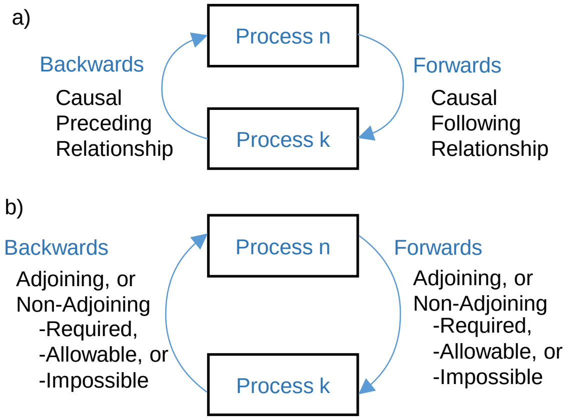


Figure 4.6: Process causal relationship network. a) distinction of composable requirements for forward and backward methods, and b) relationship network construction.

A forward requirement can be thought of as observing the final state, the current state, and identifying what must occur to reach the final state. For example, when starting with a stock of material a volume must be removed to reach the final state, this can be accomplished with a material removal process and thus limits selection of UMPs. Another forward looking method is to designate that one specific UMP always follows another. For example, a hardness inspection process (e.g. Rockwell test) must always follow a material hardening process (e.g., shot peening). A backward requirement can be thought of as observing the final state, then identifying a current state to start from. For example, after identifying a cone as the final state, the initial state and transformation method can be identified as casting the final state, or extruding an intermediate state and turning for the final state. Another backward looking method is to designate that one specific UMP must always precede another. For example, a degreasing process and cleaning process (e.g. vapor degrease and rinse) must always occur before a surface defect inspection process (e.g. penetrant test). Finally, the distinction between backwards and forwards methods is that a forward method already has designated the current state and whereas backward method does not. Implementation of this idea would be similar to the ontologies based on descriptive predicate based logic as found in [214]. A causal process network can be built using ontology software, for example *protégé*© (http://protege.stanford.edu/).

4.4.2 Manufacturing Process Taxonomy

The process taxonomy developed here (Figure 4.7) is similar to previously develop taxonomies, e.g., [13], [18], [19], but this UMP taxonomy differs to aid in conceptual reasoning of the UMP-workpiece interaction, and the identified function of the UMP. First, metals synthesis has been included as a category of UMPs, and is included to capture upstream manufacturing unlike other taxonomies; this category should be expanded to materials synthesis to capture all materials in Figure 4.11. Second, the bulk of discrete part UMPs are divided into either the geometry modification or the property modification category, and these are seen to be side by side rather than vertically stacked in Figure 4.7. This identifies that geometry and then property modification does not occur linearly in every manufacturing application, whereas synthesis always occurs first. Finally, joining is the last category of UMPs, and is so because components are only joined together after they have achieved a specified geometry and exhibit specified properties. Notwithstanding, this rule is broken, for example, when holes are reamed to ensure hole alignment or when additional features are added for additional joining UMPs.

Material Synthesis

Mineral Extraction	Surface Mining, Sub-Surface Mining
Agglomeration	Pelletizing, Sintering

Mineral Dressing	Comminution, Separation
Reduction and Refining	Pyrometallurgy, Hydrometallurgy, Electrometallurgy

Geometry Modification

Initial Forming: Consolidation	Casting, Molding, Compacting, Deposition, Laminating
Mass Conserving	Forging, Extruding, Drawing, Rolling, Bending
Mass Reducing	Reducing (chips), Separating (shear), Torch Cutting, EDM, HEBM, Chemical Milling, ECM, PCM

Properties Modification

Heat Treatment	Recovery Annealing, Recrystallization Annealing, Surface Hardening, Through Hardening, Sintering, Cold Treatments, Curing/Bonding
Surface Coating	Pressurized Spray Coating, Charged Spray Coating, Dip Coating, Flame Spraying, Heat Tinting, Vaporized Metal Coating, Electro Plating, Chemical Conversion
Surface Preparation	Descaling, Deburring, Degreasing
Surface Modification	Burnishing, Peening, Texturing

Joining

Reversible	Mechanical, Fastening

Non-Reversible	Thermal Welding, Brazing, Soldering, Adhesive Bonding

Figure 4.7: Taxonomy of manufacturing processes for metals, adapted from [13], [19], [215]

Overcash et al. [36] also investigated altering the UMP taxonomies, but was limited to comparison of differing taxonomies and included joining as a shaping process, whereas shaping UMPs are in the geometry modification category and joining is its own category in the taxonomy herein. Groover [19] identified UMPs similarly (geometry/properties/joining) but with a narrower scope, the difference herein is any surface affecting processes are included within property modification and were not in Groover. As identified by Tilley [216], external surfaces of solids may dominate the properties of the sample. Thus surface coating, surface preparation, surface modification have been included within the property modification category. This is not to say the material underneath the surface has changed properties, but the overall workpiece exhibits those surface properties. The same argument holds true for surface preparation processes, i.e., the mechanism of action (force) holding the property changing material to the surface of the component should not influence the categorical designation of the process, e.g., grease held on by capillary forces should be within equal category to paint held by chemical bond forces, and thus a greasing process and a painting process are both property modification processes.

Groche et al. [217] investigated mechanical joining UMPs, and sub-divided into the two mechanisms form-closed and force closed, and included a non-mechanical mechanism as metallurgical joints. Ageorges et al. [218] investigated joining of composite materials and identified that there are possible new categories for joining of dissimilar materials, e.g. the use of thermoplastics as hot melt adhesives. Additionally, Ageorges et al. [218] identified pre-treatments, categorized fusion bonding into bulk heating, frictional heating, electromagnetic heating, and two-stage techniques. Whereas Yousefpour et al. [219] categorized fusion bonding into thermal, friction, or electromagnetic welding. Amancio-Filho and dos Santos [220] confirm that joining is still growing, their review of polymer-metal hybrid structures identifies hybrid joining methods: weld-bonding, riv-bonding, clinch-bonding, and “glue and screw”.

A UMP is not only identified by the equipment taxonomies identified in Figure 4.7. A UMP can also be identified by its function, an shown in Figure 4.8. The function of a UMP is defined as the value adding transformation the workpiece undergoes that is caused by a UMP. Note that Figure 4.8 does not include the synthesis processes, nor does it provide detail on joining, both of these are areas of future work.

4.4.3 Unit Manufacturing Process Characterization

Generic UMP models have been developed by Kellens et al. [34], [35], Overcash et al. [99], Branham et al. [221], and Gutowski et al. [222]. The generic UMP models developed previously only identify environmental performance of the UMPs. The evaluation criteria characterized is either energy or mass transformations, input or output.

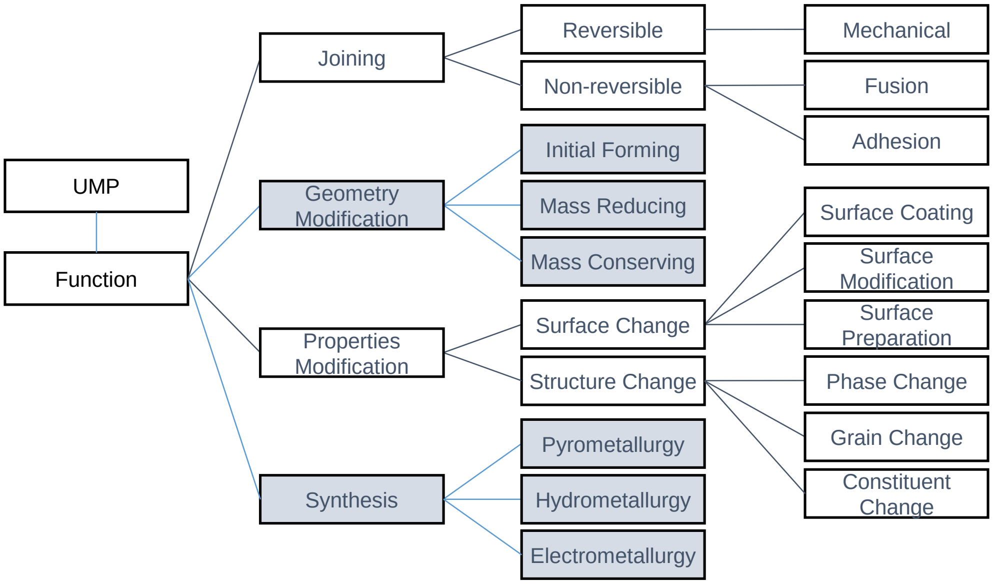


Figure 4.8: Unit manufacturing process functions adapted from [7]–[9], [15]. Shading for visual clarity.

A generic UMP that incorporates economic, environmental, and social aspects has not been developed. Figure 4.1 shows a UMP that incorporates all three sustainability aspects as inputs and outputs. Furthermore this section will develop a generic UMP mathematical model, but a discussion on functional unit and process boundary is undertaken to aid in UMP modeling conceptualization.

When developing a UMP characterization, one objective is to account for all evaluation criteria in reference to the functional unit of the process. A functional unit for a unit process is usually some instantaneous increment of the transformation of the UMP, e.g., milling would be one cubic centimeter of material removed [34]. Furthermore, all evaluation criteria are normalized to this functional unit to create a unit process lifecycle inventory (UPLCI). Defining a functional unit is critical to characterization because it allows for referenced comparison of other UMPs, and enables normalization of individual UMPs. Normalization to the functional unit is not always directly applicable, but can be implicitly accomplished. One example for implicit normalization is using the time to process the functional unit. An example is a social criteria like the injuries per product, this is challenging to quantify in terms of the functional unit of the processes but it can be by calculating average injury rates from a dataset (from a business or government organization, e.g. the Bureau of Labor Statistics (BLS)) and normalizing injury rates to the processing time of the functional unit.

Another critical aspect of a UMP model is the process boundary. The process boundary should relate to the physical aspects of the UMP, e.g., the footprint, and can loosely be identified as, "where one process starts and the previous stops." But this is not correct because it includes the transportation and storage between the processes as being within the bounds of the prior process. Transportation and storage are not usually modeled as UMPs because they provide no value added transformation to the workpiece, see the NRC definition of a UMP. But these two activities do have some impact that can be quantified, e.g., forklift transportation does require an energy source, and there are the standard storage costs. Thus, when defining and evaluating UMP boundaries, it is necessary to identify non-transformation processes as well to capture all the boundaries within a MPF. But this is not to say that all non-transformation processes should be modeled and included within calculations, but rather should be taken note of for appropriate impact allocation.

Figure 4.1 has been adapted to Figure 4.9 to further differentiate the aspects of a UMP. Figure 4.9 shows the UMP resources, liabilities, process information, and feedback as the current state of the UMP. A UMP current state is variable, and thus the characterization of a UMP will change over time. Furthermore, the function of the UMP is identified separate of the current state, which is to say that the UMP function does not change over time (unless the UMP is heavily modified) whereas the sustainability impact will in reference to the current state.

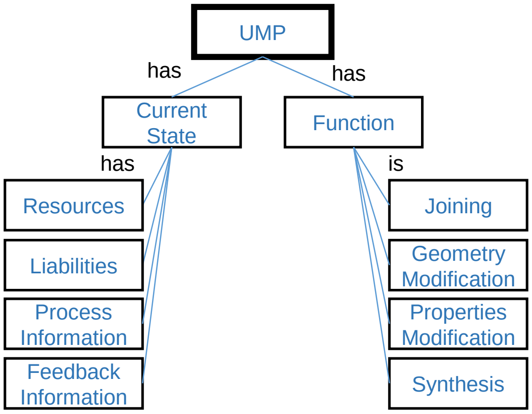


Figure 4.9: UMP characterization model

The UMP function is related to the designation in the UMP taxonomy in Figure 4.7 and the transformation that occurs to the workpiece in Figure 4.8. Note that this representation is made for those UMPs in the taxonomy in Figure 4.7, and does not include details for other UMPs, e.g., chemical UMPs that may have and recollect output energy.

The lofty goal of this section was to develop an all-encompassing UMP model, but this is not realistically possible. UMP models quantify specific evaluation criteria (metrics in this case) for unique UMPs. Predetermining the evaluation criteria restricts the generalizability of a UMP model. But to create generalized models, evaluation criteria must be predetermined and thus several examples are seen below in Equations 4.1 – 4.9. These equations were developed through analysis of many UMPs, IDEF0 diagrams developed from those UMP models can be found in Appendix A. The generalized equations are constructed to capture operating impacts of manufacturing processes and do not include investment impacts or retirement impacts of manufacturing equipment, devices, and mechanisms. The impacts capture the economic, environmental, and social aspects of sustainability, and can be seen in Table 4.1.

Table 4.1: Evaluation criteria selected for UMP models

Aspect	Evaluation Criteria	Unit
Economic	Operating Cost	Dollars
Environmental	Energy Consumption	Kilowatt hours
	Water Use	Liters
	GHG Emissions	Kilograms carbon dioxide equivalent
	Total Waste	Kilograms
Social	Average Wage	Dollars per hour
	Lost Work Days	Number of days

A single economic impact is accounted for, operating cost seen in Equation 4.1. Operating cost is the only economic metric included here because costs relate directly to company profits and an unprofitable company cannot act competitively. The equation accounts for consumables costs, energy costs, and labor costs; consumables include any mass that flows into the process excluding the workpiece.

$$\text{Operating Cost (\$)} = \text{Mass}_{\text{consumables}}*\text{Cost}_{\text{consumables}} + \text{UseRate}_{\text{consumables}}*\text{Time}_{\text{process}}*\text{Cost}_{\text{consumables}} + \text{Energy}_{\text{consumed}}*\text{Cost}_{\text{energy}} + \text{Water}_{\text{consumed}}*(\text{Cost}_{\text{Water}}+\text{Cost}_{\text{waste water}}) + \text{Waste}_{\text{total}}*\text{Cost}_{\text{waste disposal}} + \text{Time}_{\text{process}}*\text{Cost}_{\text{labor}} \quad (4.1)$$

Environmental impacts identifies include energy consumption, water use, greenhouse gas (GHG) emissions, and total waste. These metrics were selected to capture the wider array of environmental impacts applicable to UMPs. Many of the parameters identified for the equations can be either derived from mechanics or thermodynamics or can be monitored using data collection devices, e.g., Equations 4.2, 4.3, and 4.5. Another method for evaluating metrics is to convert known quantities using historical data, e.g. Equation 4.4 converts energy into GHG emissions using historical energy production data. Finally, Equation 4.6 identifies several different units that it can take, and this is dependent on the function of the UMP being modeled. Note, that material processed is not identified as an evaluation criteria but is instead used to calculating other metrics.

$$\text{Energy Consumption (kWh)} = [\text{Power}_{\text{workpiece\_geometry}} + \text{Power}_{\text{process\_parameters}} + \text{Power}_{\text{empirical}}]*\text{Time}_{\text{process}} \quad (4.2)$$

$$\text{Water Use (L)} = \text{Rate}_{\text{water\_use}}\,(\text{Time}_{\text{BTRF}}*\text{Volume}_{\text{tank}}*\text{Percent}_{\text{water}})*\text{Time}_{\text{process}} + \text{Rate}_{\text{water\_use}}(\text{Rate}_{\text{dragout}}*\text{Percent}_{\text{water}})*\text{Time}_{\text{process}} \quad (4.3)$$

$$\text{GHG Emissions (kg)} = \text{Energy}_{\text{consumed}} * (\text{Rate}_{\text{CO2}} + \text{Rate}_{\text{CH4}} * \text{GWP}_{\text{CH4}} + \text{Rate}_{\text{N2O}} * \text{GWP}_{\text{N2O}}) + \text{Emissions}_{\text{direct\_combustion}} + \text{Emissions}_{\text{direct\_vaporization}} \tag{4.4}$$

$$\text{Total Waste (kg)} = \text{Mass}_{\text{consumable}} * \text{Rate}_{\text{comsumable\_per\_part}} * \text{Material}_{\text{processed}} + \text{Rate}_{\text{waste}} * (\text{Time}_{\text{BTRF}} * \text{Volume}_{\text{tank}} * \text{Percent}_{\text{non-water}}) * \text{Time}_{\text{process}} \tag{4.5}$$

$$\text{Material Processed (kg, m}^3\text{, m}^2\text{)} = \text{Rate}_{\text{material process}} * \text{Time}_{\text{process}} \tag{4.6}$$

The social evaluation criteria identified here includes lost work days and average wage. Two models are presented for lost work days (Equations 4.7 and 4.8), the first counts the number of days lost for each injury or illness for a UMP, while the second uses probability of injury or illness and the likely length of time not working. One can either assume a probability distribution, fit injury and illness data to a probability distribution. The Poisson distribution counts the number of events within a given time interval [223], and can be used for the probability of injuries at a UMP. The triangular distribution estimates that a random variable has a most common value situated between a high and a low value and is used as a substitute for more complex distributions [224]; the triangular distribution can be used for the number of days lost. Others have used the log-normal for illnesses [225], a novel model for injuries [226], and the Weibull distribution and the Singh-Maddal distribution for time unemployed [226]. Also Crook and Moldofsky presented data on likelihood of return to work [227]. Average wage, Equation 4.9, normalizes the wage of individual employees working at each UMP to an average for that UMP. Average wage then accounts for multiple employees at a single UMP or multiple equivalent UMPs in a facility. In either case, wages are averaged by labor time for each employee at a UMP.

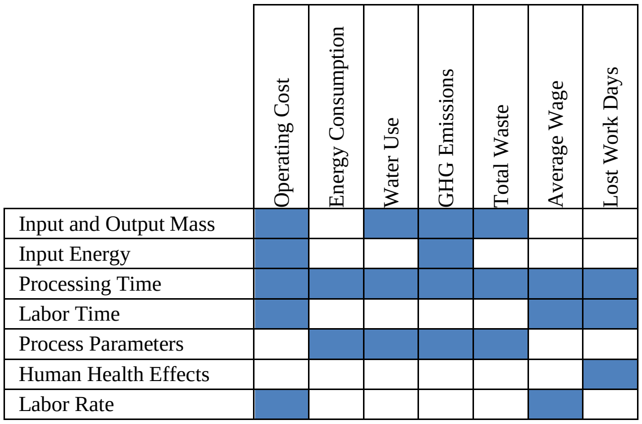
$$\text{Lost Work Days} = \sum \text{Illness\_i}_{\text{Number\_of}} * \text{Days\_Lost}_{\text{i}} + \sum \text{Injury\_j}_{\text{Number\_of}} * \text{Days\_Lost}_{\text{j}} \tag{4.7}$$

$$\text{Lost Work Days} = \sum \text{Probability}_{\text{Illness\_injury\_k}} * \text{Probability\_}_{\text{Days\_Lost\_l}} \tag{4.8}$$

$$\text{Average Wage (\$)} = (1/\text{Time}_{\text{process}}) * \sum \text{Wage}_{\text{Laborer\_k}} * \text{Time}_{\text{Laborer\_k}} \quad (4.9)$$

Joung et al. [228] included technological impact as an additional aspect of sustainability, and identified that the Japan Science and Technology Agency (JST) [229] was early to incorporate technology aspects into sustainability assessment. Dornfeld and Wright [230] identified that additional impacts in manufacturing technology should be undertaken to reduce impacts elsewhere in a product lifecycle. Developing mathematical models for capturing technological impact of UMPs will remain an aspect for future work. Measureable technological aspects might include the required knowledge, or the producing ability of the process. Required knowledge (years of training) for operating a process, or required oversight of the process (e.g. operable by untrained persons, but quality products require highly knowledgeable oversight). Improvements upon previous technology, this can be compared using the other three aspects of sustainability, e.g. Dewulf et al. [231] quantified the technology improvements with exergy and this same concept can be historically seen with aluminum production and the Hall-Heurolt process [232]. Joung et al. [228] also identify that technology improvements are also quantifiable by observing the functions or products that are producible because of the process. Finally, one could measure technology by the observing how complicated it is, e.g. measuring the number of patents cited [233]. Incorporating technological aspects into UMP modeling is included in future work.

Similar to identifying generalized models from predetermined metrics, one can identify specific data required to model a majority of UMPs. As seen in Figure 4.10, when analyzing the mathematical models developed prior, common measurements are identified that are widely applicable to modeling the three aspects of sustainability for characterizing the operations of manufacturing processes. The measurements identified are specifically left vague to allow for wide applicability, e.g., the measurements input and output mass, processing time, and process parameters will be different for each UMP and would hold a unique data spot in an information model or database.



	Operating Cost	Energy Consumption	Water Use	GHG Emissions	Total Waste	Average Wage	Lost Work Days
Input and Output Mass	■		■	■	■		
Input Energy	■			■			
Processing Time	■	■	■	■	■	■	■
Labor Time	■					■	■
Process Parameters		■	■	■	■		
Human Health Effects							■
Labor Rate	■					■	

Figure 4.10: Unit process measurements generalizable to process performance metrics

The figure identifies the use of several generic unit process measurements that when integrated together can quantify several example performance metrics. The unit process measurements are identified in a way to allow for broad applicability to a variety of UMPs. Identifying this generic set allows for a broad set of performance metrics applicable to specific UMPs to be analyzed with a standard data set. That said, each of the unit process measurements will generate enough unique results that the data set is only standardized at this higher level. In sum, UMP characterization is carried out by both cataloguing all process information with a structured method and generating equations to relate evaluation criteria to measurable UMP information.

4.4.4 Workpiece characterization

There is a fundamental difference between workpiece characterization and process characterization. While process characterization is used to instantiate the impacts of the unit process, workpiece characterization is used to instantiate the material response to the manufacturing transformation. Using the term material model would be a misnomer, and should be avoided as multiple representations are needed to capture the information that is contained within a workpiece during any instant throughout a manufacturing system. The four aspects of workpiece characterization are the current state, final state, properties, and geometry. In workpiece characterization, the desired state is the final state of the workpiece as described during the design of a product. The current state is used to track the workpiece as if travels through an MPF and will change with each subsequent UMP. These changes are reflected as either a property transformation or a geometry transformation. Note there are some UMPs that will do both, e.g. cold rolling. Thus modeling the resulting transformation of workpiece by the UMP enables the linkage between independent UMP models.

Feng [234] and Gupta et al. [235] have both developed classifications for modeling the geometry features of a workpiece. Furthermore, both Sarigecili et al. [236] and Hunter et al. [237] have developed methods and ontologies for automating inspection processes utilizing geometric dimensioning and tolerancing (GD&T). Zhao et al. [238] developed an ontology for representing GD&T to enable integrated measurement techniques. Zhong et al. [239] developed a similar ontology for representing GD&T to enable automatic tolerance identification unique to assemblies. Ahmed and Han [240] have developed a geometry representation ontology to avoid semantic mismatches in interoperability. Thus it is apparent that geometry based approaches to workpiece modeling have been undertaken by previous authors, and incorporating this modeling aspect is outside the scope of this work.

Material science utilizes tensors to relate different material properties to one another. When a material space group is analyzed in correspondence with a the tensor property, material scientists can identify if a material will exhibit a specific property [241]. Tensor properties are identified in Figure 4.11 below to represent properties that are unique to specific material due to the symmetry of their crystal system and space group, e.g. piezoelectricity. But, property derivation using spacegroup analysis is outside the context of this work. Many other properties are inherent to all materials, e.g. hardness and strength, and this is reflected in Figure 4.11. Nonetheless, Figure 4.12 shows the material modeling structure that can be utilized for this application. Figure 4.12 can be used for expanding to incorporate material analysis for specific properties.

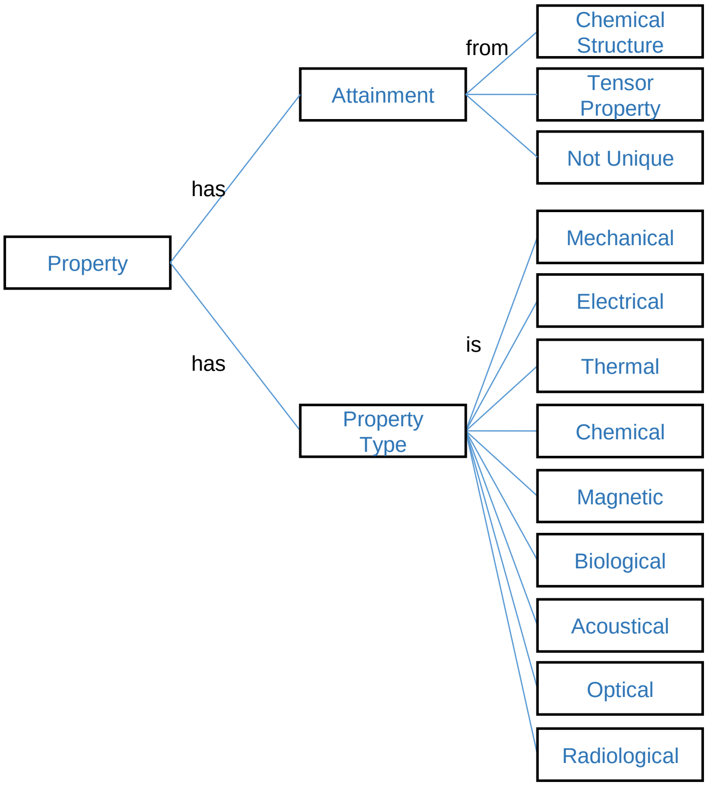


Figure 4.11: Property taxonomy; adapted from Chung et al. [242].

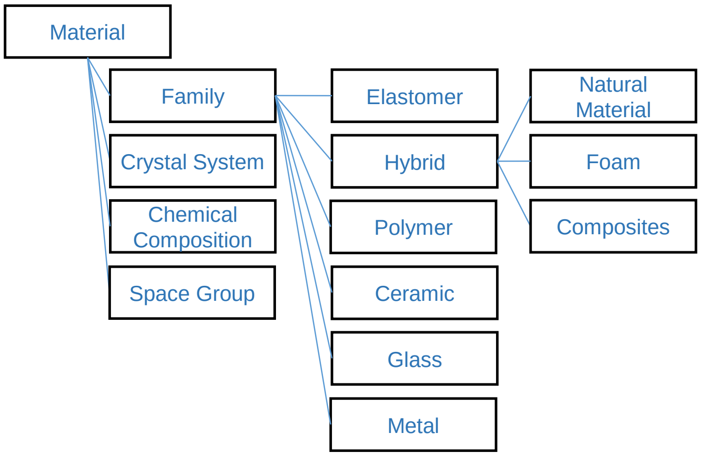


Figure 4.12: Material taxonomy (adapted from Ashby 2011 [126] and Chung et al. [242]).

The workpiece model can be seen in Figure 4.13a. This model identifies the current state and the final state. The geometries and properties are identified as specific features of the workpiece, and each workpiece can consist of multiple features (Figure 4.13b). Properties and geometry are captured as features, dividing up the workpiece into regions. A default feature (the bulk) can be designated, that makes up non-specified regions and the core, in the case of surface features. Thus, identifying the uniqueness of each feature is only required. Finally, the workpiece is a component of some product, and this is included as well for future joining processes. Each feature identifies a constituent material to account for addition processes, e.g. a paint coating. The unique properties of the material are recorded in under the properties of the feature because the workpiece will now exhibit those properties. Finally, each feature is given a unique name.

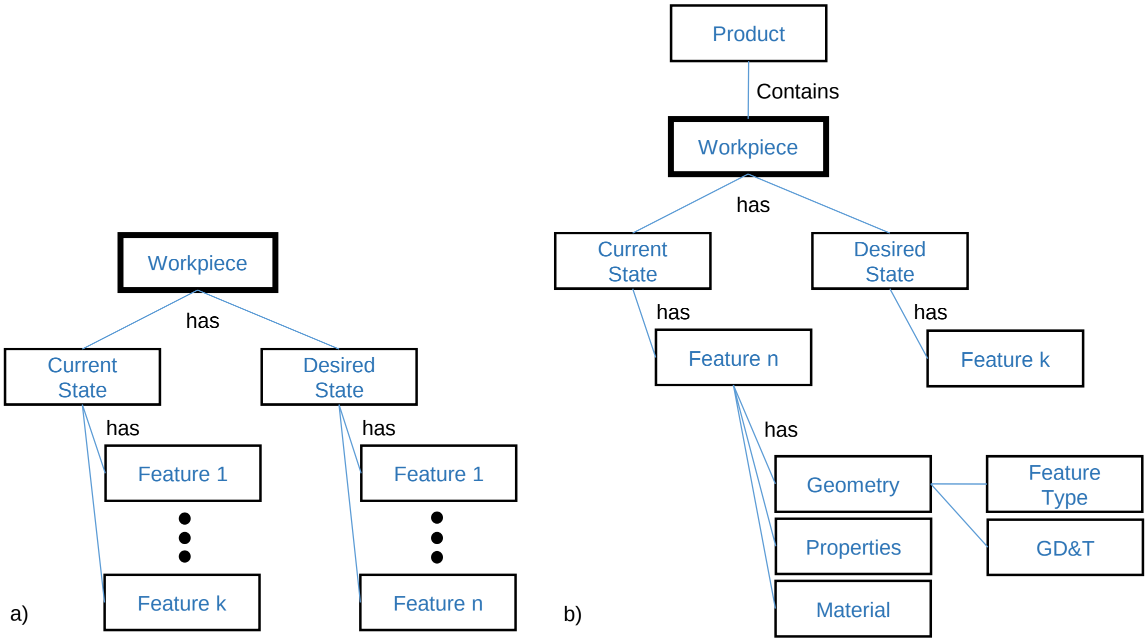


Figure 4.13: Workpiece characterization model. a) representation of workpiece states containing multiple features, and b) description of all attributes.

4.4.5 UMP Workpiece Relationship

The crux of the work, how does one link the workpiece to the UMP? This is accomplished with two methods. First, is to link using the function of the UMP to the transformation that occurs to the workpiece. Second, is to link using the different characterizations required to characterize UMPs and calculate evaluation criteria. The first relationship appears stronger, because it is tangible and relates to the fundamental principle of manufacturing, which is to create valuable products. The second while a less tangible interaction, allows us to evaluate modern manufacturing goals including MCDA sustainability analyses.

The UMP-workpiece function relationship is shown in Figure 4.14. This relationship is designated by the transformation that occurs to the workpiece, i.e. how the UMP modifies the workpiece. Modifications are unique to the function of the UMP, and thus UMPs are organized by function. While there are many different UMPs, not all UMPs have a unique function, thus some functions are shared by UMPs. Identifying the different functions of UMPs is accomplished at a high level in Figure 4.8. Figure 4.8 can be expanded to identify all possible modifications, and thus create a more detailed taxonomy; the material science research area would be a good starting place. An ontology of UMP functions is provided in Figure 4.8, which is similar in form to the device function ontology created by Kitamura and Mizoguchi [243].

The use of UMP characterization is the calculation of evaluation criteria for process, product, and plant analysis and improvement. To evaluate criteria, calculation variables are used and are subdivided into control information, measurements, or literature data. The subdivision of calculation variables are mapped to different UMP state information and workpiece state information, substantiating the available manufacturing information. Thus the workpiece and UMP information interacts in evaluation criteria calculations, as shown in Figure 4.15 and examined in Section 4.4.3.

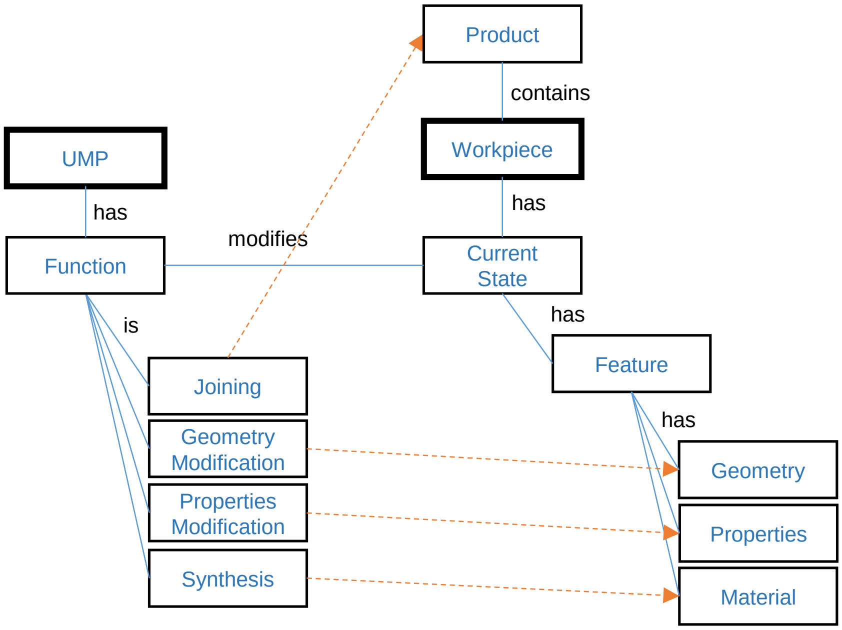


Figure 4.14: UMP-workpiece function relation, dashed arrows indicate which UMP functions modify specific workpiece states

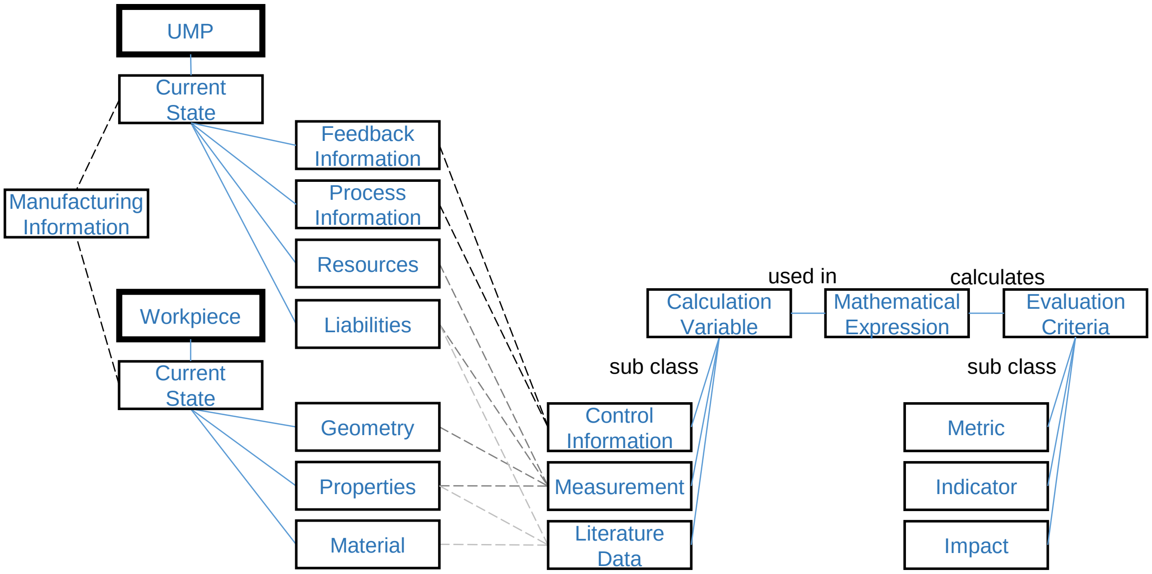


Figure 4.15: Information flow for UMP-workpiece characterization, dashed lines indicate categorization of information

The evaluation criteria are used to influence or guide change with in the manufacturing system, see Figure 4.16. Here the manufacturing system has two states, being the current state and the final state. The manufacturing system is designated by three different levels, being the individual processes, the products (a MPF), and the plant (entire facility). The selection of the system level is designated by an improvement team or analyzer.

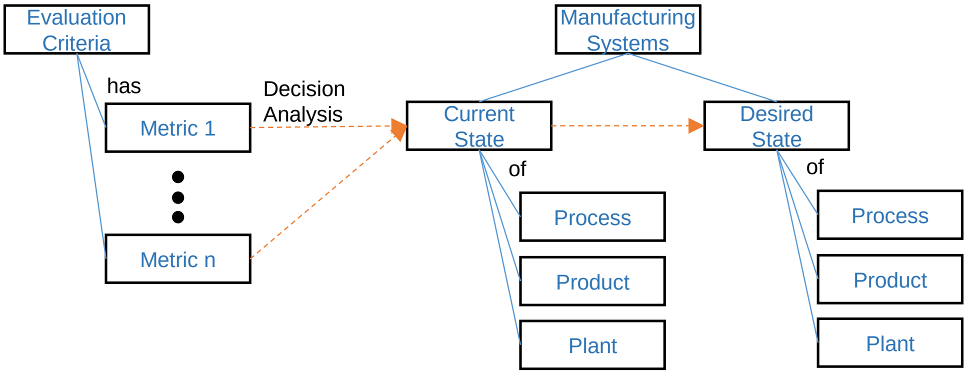


Figure 4.16: Implementation of change to the manufacturing system

4.5 An Application in Mathematical Modeling

An example manufacturing process flow is presented below that utilizes the workpiece state by identifying the change of the ultimate tensile strength (UTS), σ_{uts}, and the thickness of the workpiece by subsequent UMPs. The example also demonstrates how changing the process parameters in one UMP can affect the sustainability performance of a subsequent UMP, as shown in Figure 4.4. The example MPF is Figure 4.17, which identifies each workpiece state along with each UMP that transforms the workpiece. The flow developed in Figure 4.17 is described in the subsections below. Section 5.4.1, identifies the 0 State (initial state) and F State (final state) of the workpiece. Sections 5.4.2-5.4.4 describe the UMP and the effect on the immediately following workpiece state; these sections relate the process settings to the effect on the workpiece. Because the MPF is driven by the final workpiece state, State F is identified before the MPF and is in

Section 4.5.1 along with State 0 For brevity, not all calculations are shown here, but can be found in Appendix B.

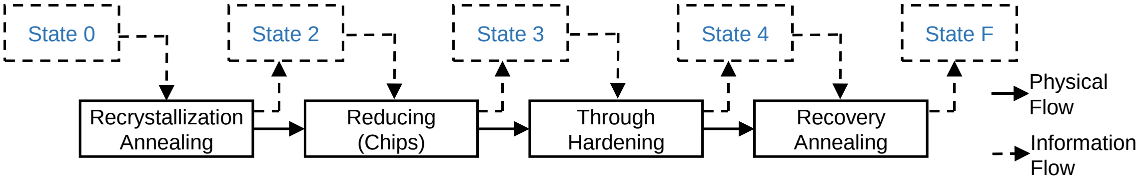


Figure 4.17: An example manufacturing process flow

Table 4.2 summarizes the variables and transformations for each UMP in the example MPF. The UMP variables are related to the workpiece variables and drive the process parameters and the evaluation criteria, as demonstrated below. A steel alloy (SAE 4340) is used as the workpiece material, and thus the workpiece transformation infomation identifies the steel crystal structure (material) changes and the part geometry (shape) changes.

Table 4.2: UMP-workpiece relationships

Section	**UMP Name**	**UMP Variables**	**Workpiece Variables**	**Workpiece Transformation**
4.5.2	Recrystallization Annealing	Cooling rate, time, temperature	Thickness	Formation of pearlite
4.5.3	Reducing (Chipping)	Cutting force, cutting time	Ultimate tensile strength	Removal of material (chips)
4.5.4	Through Hardening	Cooling rate, time, temperature	Thickness	Formation of martensite
4.5.5	Recovery Annealing	Cooling rate, time, temperature	Yield strength	Formation of ferrite

4.5.1 Workpiece State 0 and State F

The 0 and F states of the workpiece are identified prior to developing any MPF. The MPF is used to transition and add value (reaching State F) to some lower-valuable product (State 0). The 0 State and the F State are identified below.

The 0 State of the workpiece is identified in Figure 4.18a. The 0 State is the stock material and is defined as the bulk of the workpiece – herein the bulk is defined to be the constituent material that is beneath the surface; e.g. surface hardening gear teeth is performed to a few millimeters while the bulk of the material remains unchanged. All geometry and material properties that are exhibited through the entire workpiece affect the bulk. The bulk is identified as the 0 State, and each feature added to the workpiece in general affects the bulk. Surface properties (e.g. surface coatings) do not affecting the bulk, but will still alter the properties exhibited by the entire workpiece [216]. The bulk is used to identify the different characteristics exhibited by the surface of a part and constituent material of the part.

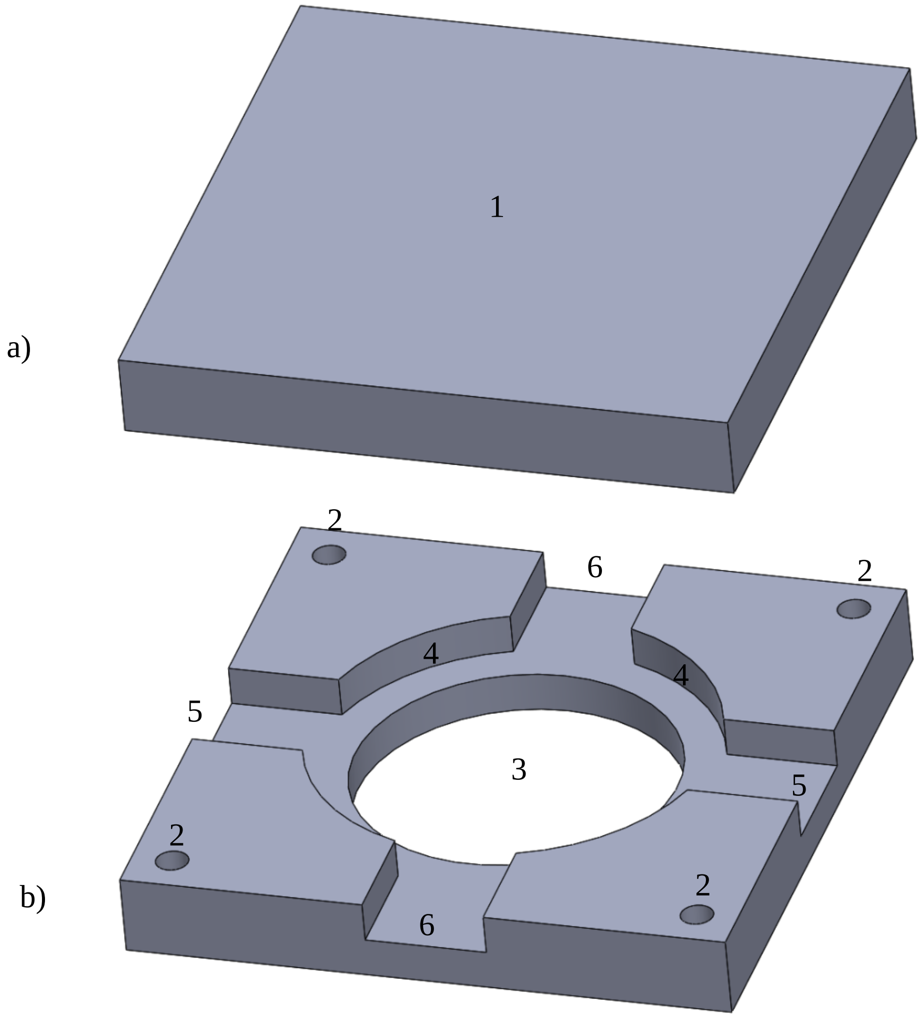


Figure 4.18: a) workpiece 0 State, b) workpiece F State. Labels correspond to features in Table 4.3.

The workpiece F State is specified by the component designer and exhibits the specified geometric features and material properties. The F State can be seen in Figure 4.18b. This is seen to have four circular holes, one at each corner; a larger center circular hole; a circular pocket, and two perpendicular slots. Of course these identifiers are only apparent if each features is cut on a fresh blank, but note volume measurements in Table 4.3 do not double count. The final component also exhibits the same bulk feature, identifying the bulk material, which exhibits the final hardness and strength properties. Finally, the features and a simplified account of their geometric shape and material properties are provided in Table 4.3.

Table 4.3: Features of the F State

Feature	**Name**	**Geometry**	**Properties**	**Measurement**
1	Bulk	--	Hardness	135 Hv
--	--	--	Yield Strength	300 MPa
2	Corner Circular Holes	Volume	--	205.89 cm^3
3	Center Circular Hole	Volume	--	4.12 cm^3
4	Circular Pocket	Volume	--	156.88 cm^3
5	Slot 1	Volume	--	63.42 cm^3
6	Slot 2	Volume	--	63.42 cm^3

4.5.2 Recrystallization Annealing UMP and Workpiece State 2

4.5.2.1 Recrystallization Annealing UMP

The first process identified in the MPF is a full recrystalization annealing process. Annealing has of a causal relationship with the subsequent reducing process (Figure 4.19). While the 0 State geometry of the workpiece is known, the material properties of the 0 State are unknown. The reducing process (Section 4.5.3) requires a specified UTS for modeling the cutting forces, thus necessitating an annealing step prior to macining. The function of the annealing UMP is to reduce the strength and hardness of the workpiece, to reduce cutting forces and increase cutting tool life in the subsequent reducing UMP, which will improve economic feasibility and process yield. The recrystallization annealing UMP causes the formation of pearlite in steel, which is layered lamellae of cementite and ferrite [244].

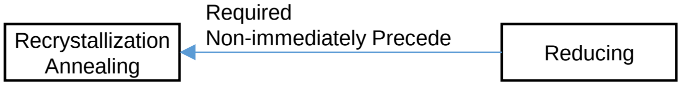


Figure 4.19: Causal relationship between the reducing and recrystallization annealing UMPs

Heat treatments typically undergo heating, maintaining, and cooling regimes. For the purposes of this example, it is assumed that the oven operates continuously, parts are processed in batches, and that parts are removed from the oven for air cooling. Thus, the process energy use is modeled by calculating the amount of total heating energy allocated to each part on a volume basis. The formulation for process energy use is shown in Equation 4.10. The calculations for each heat transfer were developed based on work by Canada EMR [245] and Kaminski and Jensen [246]. Also, while different oven types, e.g., bath ovens or continuous ovens, can be used for certain applications, the equipment identified here is a common insulated, air environment oven. Thus, energy required for the oven can be derived for heating the volume of air and the part for the specified process time. Energy sources will vary with different equipment, and even with a common oven, different energy sources (e.g., electric or natural gas) will have different energy to heat conversion efficiencies. The annealing time is set to two hours to allow for full austenization of the steel [247], as identified in Equation 4.11. Krauss [244] identified that the austenization temperature about 50 ^{o}C above the a3 temperature for a particular steel composition, the ASM handbook [247] identified 840 ^{o}C for SAE 4340 steel.

$$\text{Energy}_{\text{total\_required\_oven}}\ (\text{J}) = (\text{Heat}_{\text{oven\_wall\_loss}} + \text{Heat}_{\text{flue\_gas\_loss}} + \text{Heat}_{\text{Convection}} + \text{Heat}_{\text{Radiation}}) \\ {}^{*}\text{Time}_{\text{process}} + \text{Energy}_{\text{part\_caryoff}} \qquad (4.10)$$

$$\text{Time}_{\text{Austenization}}\ (\text{t}) = \text{Time}_{\text{perThickness}} * \text{Thickness}_{\text{Component}} \qquad (4.11)$$

4.5.2.2 Workpiece State 2

UTS is an important property that is desired and used in the reducing models. As discussed in Section 4.5.3, the UTS is related to the shear stress of a material and determines the cutting force. A material with a lower UTS will require a lower cutting force, thus the current workpiece state is updated to modify the UTS of the bulk feature. Modeling hardenability and prediction of steel strength and hardness from different heat treatments has been previously reported. This work implements the Creusot-Loire System as developed by Maynier et al. [248] and re-implemented by Trzaska et al. [249]. This method is limited in range of composition (the maximums are: C<0.77, Mn<2.04, Si<1.90, Cr<2.08, Ni<3.65, Mo<1.24, V<0.36, Cu<0.3). Other approaches could be employed. An alternative method, first developed by Kirkaldy and Venugopalan [250], then improved by Li et al. [251], may yield increased accuracy. In the method employed, the hardness is calculated as a function of percent martensite, banite, and pearlite-ferrite ($\%_i$) formed and the equivalent hardness (Hv_i) of each phase (Equation 4.12)

$$Hv\ (kg_f/mm^2) = \%_M * Hv_M + \%_B * Hv_B + (\%_F + \%_P) * Hv_{FP} \tag{4.12}$$

The resulting hardness is then converted to ultimate tensile strength (UTS, σ_{UTS}) using the model developed by Pavlina and Van Tyne [252] (Equation 4.13); where Hv is Vickers diamond pyramid hardness (kgf/mm^2).

$$\sigma_{UTS}\ (MPa) = -99.8 + 3.734 * Hv \tag{4.13}$$

4.5.3 Reducing (chipping) UMP and Workpiece State 3

4.5.3.1 Reducing (chipping) UMP

The second process in the example MPF is the reducing UMP, which is accomplished using a milling machine. Milling is suitable for material removal in non-rotational parts, as considered here. All of the features are quarter inch or greater in diameter and thus can completed using a single setup and cutting tool; realistically roughing and finishing would be split into multiple. The machining UMP here uses commonly derived predictive force equations from the Merchant model [253]. The Merchant model stipulates that a shear plane angle exists at which the applied shear stress is equivalent to the shear strength of that material being cut. The shear strength can then be estimated from the UTS of the material. Applying this concept to the manufacturing of steel products, one can foreseeably predict the force required to cut the material after given a heat treatment operation to estimate the material UTS. An alternative method would be to link material removal rate (MRR) to hardness or UTS (to link to the hardening model in Section 4.5.2.2) and then utilize the work by Diaz and Dornfeld [254], to estimate milling energy from MRR. Milling time is calculated as an average, and is the volume of material removed (VMR) divided by the MRR, Equation 4.14.

$$t_{\_reduce} = VMR/MRR \tag{4.14}$$

Starting with the UTS of Workpiece State 2, the shear force (F_s) can be calculated as a function of the UTS, which can then be used to determine the cutting (F_c) and thrust (F_t) forces (equations 4.15 and 4.16). This is because the shear strength of the material can be estimated as a fraction (0.7) of the UTS, and the shear force is a product of the shear stress (τ) and area of the shear zone (As) [19]. The derivative of cutting and thrusting forces are shown in Equations 4.15 and 4.15 and are the stresses applied in the cutting and thrusting directions.

$$dFc\ (kg*m/s) = 0.7*\sigma_{UTS}*As*\cos(\beta-\alpha)/\sin(\varphi)*\cos(\varphi+\beta-\alpha) \tag{4.15}$$

$$dFt\ (kg*m/s) = 0.7*\sigma_{UTS}*As*\sin(\beta-\alpha)/\sin(\varphi)*\cos(\varphi+\beta-\alpha) \tag{4.16}$$

Where β is the friction angle, α is the rake angle, and φ is the shear plane angle, which are dependent on the tool geometry and material properties. The cuttings forces in the X and Y directions are calculated using Equations 4.17 and 4.18 and are equations are trigonometric conversions from the thrusting and cutting forces dependent on the angle of the engaged tooth (θ_R).

$$dFx\ (kg*m/s) = -dFc*\cos(\theta_R) - dFt*\sin(\theta_R) \tag{4.17}$$

$$dFy\ (kg*m/s) = dFc*\sin(\theta_R) - dFt*\cos(\theta_R) \tag{4.18}$$

Table 4.4: Comparison of machining power and cutting efficiency

Machining Power (W)	Cutting Efficiency (%)	Machine Type	Author
3000	-	Turning	Kara and Li [255]
1600-2000	17.5-34.3	Milling	Diaz et al. [256]
650-900	9-18	Milling	Li et al. [257]
700	-	Milling	Yan and Li [258]
1000-1300	-	Turning and Milling	Wang et al. [259]
18,200	-	Drilling	Overcash et al. [99]
18,500	-	Drilling and Milling	Mori et al. [260]
4000	12.5	Turning	Balogun and Mativenga [261]
7,900-15,400	13.6-49.4	Milling	Avram and Xirouchakis [262]
-	48.1, 65.8, 69.4	Milling	Kordonowy [263]
-	14.8	Milling	Dahmus and Gutowski [30]
-	25	Machining	Dietmair and Verl [264]

The theoretical energy to cut a material is then a product of the cutting force, the teeth per cutter (Nt), the cutting velocity ($Feed_{perSecond}$), and the cutting time ($t_{Revolution}$) (Equation 4.19). Thus the theoretical cutting energy is calculated as a function of the incremental required energy per revolution, and is multiplied by the number of revolutions ($N_{Revolutions}$) (Equation 4.19), adapted from Groover [19]. To calculate total milling energy, the cutting energy is then scaled in Equation 4.20 by the percent energy consumed during cutting, cutting efficiency seen in Table 4.4; a conservative 15% was used as the percent cutting energy in milling.

$$\mathrm{Energy}_{\mathrm{Cut}} = N_t * \mathrm{Feed}_{\mathrm{perSecond}} * \mathrm{time}_{\mathrm{Revolution}} * \int_0^{\theta} (dFx(\theta_R) + dFy(\theta_R))\, d\theta_R * N_{\mathrm{Revolutions}} \tag{4.19}$$

$$\mathrm{Energy}_{\mathrm{Mill}} = \mathrm{Energy}_{\mathrm{Cut}} / \mathrm{Percent\_Cut\_Energy} \tag{4.20}$$

4.5.3.2 Workpiece State 3

The properties of the workpiece state are assumed not to change during the reducing UMP, while work hardening will occur on the surface, this is easily ignored because the workpiece undergoes through hardening following State 3. The geometry of the workpiece state does change, the volume reduces from 922 to 493 mm^3, and the features are reported in Table 4.3 using the Feng [234] taxonomy. The thickness is one inch throughout the workpiece.

4.5.4 Through Hardening UMP and Workpiece State 4

4.5.4.1 Through Hardening UMP

The specific through hardening UMP used is quench hardening. Identification of the hardening UMP to be employed is dependent upon the causal relationship of the tempering and reducing UMPs. The F workpiece state identifies a yield strength, and the tempering UMP is identified as a process that can generate the desired strength, but the tempering UMP requires that first the workpiece undergo a hardening UMP. The F State identified a hardness value, and the through hardening UMP will exceed the desired hardness value. Thus, the recovery annealing UMP is required to follow the through hardening UMP to reduce the hardness and alleviate residual stresses. Figure 4.20 shows the causal relationship.

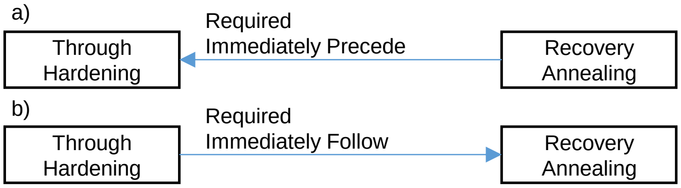


Figure 4.20: Causal relationship between recovery annealing and through hardening UMPs. a) Through hardening is required to precede recovery annealing, and b) recovery annealing is required to follow through hardening.

Through hardening time is a function of workpiece thickness; this time, still two hours are required to reach austenization because there are still areas two inches thick. The oven temperature is set to 900 ^{o}C as identified in the ASM handbook [247]. Quench can occur in water, brine, oil, air, and liquid metal [14]; water was selected to achieve the desired quench rate of 87 ^{o}C/sec for a quench time of 10 seconds. The energy calculation used for the through hardening UMP is the same as that for the recrystallization annealing UMP, and assumes that a natural gas oven is used for heating the component as described in Section 4.5.2.1.

4.5.4.2 Workpiece State 4

The resultant workpiece state from through hardening is determined using the same approach as the resultant state from annealing. The Vicker's hardness (Hv) is calculated using the Creusot-Loiere System [248], [249] and is converted to the yield strength (σ_{YS}) using the Equation 4.21 from Pavlina and Van Tyne [252]. Yield strength is used in place of UTS because the Equation 22 used to calculate intercritical temperature was empirically related to yield strength and not UTS by Tavares et al. [265].

$$\sigma_{YS}\ (\mathrm{MPa}) = -90.7+2.876*\mathrm{Hv} \tag{4.21}$$

4.5.5 Recovery Annealing UMP and Workpiece F State

To determine the energy required for the final UMP in the MPF, Recovery Annealing, first the F workpiece state is stated. The F state is used to calculate the process parameters for the final UMP and, thus, the Workpiece F State is presented before the recovery annealing UMP.

4.5.5.1 Workpiece F State

The F state is reached after the recovery annealing UMP, which decreases the hardness and brittleness and increases the toughness and ductility of the workpiece. The final workpiece yield strength is 300MPa. Equation 4.22, from Tavares et al. [265], is used to determine the intercritical temperature (Temp_IC) for tempering the steel component, assuming a recovery time of thirty minutes. An alternative method was developed by Bag et al. [266], where in the intercritical temperature is derived from the required volume fraction martensite to achieve a desired yield strength.

$$\text{Temp\_IC } (^{o}\text{C}) = (551 - \sigma_{YS})/0.454 \tag{4.22}$$

4.5.5.2 Recovery Annealing UMP

A tempering UMP is performed, and is a sub-unit of recovery annealing in the UMP taxonomy (Figure 4.7). This UMP is performed to increase the toughness and ductility and decrease hardness in a previously hardened workpiece [13], thus it is a property-altering process. The component is heated in an oven below the austenizing temperature, held for a period of time, and allowed to air cool. Like any heat treatment UMP, the sub-operations for tempering can be identified as different temperature-time regimes, but here it is simplified to a single regime. It is assumed that a natural gas oven is used to heat the component. This allows the same the input-output masses and energy calculations to be used as assumed for the recrystallization annealing UMP. The recovery temperature is the intercritical temperature identified above, and the recovery time is set to thirty minutes [265].

4.5.6 Assessment Results

The assessment results for the component considered in this demonstration are summarize in Table 4.5. Process time is a key driver for each criterion considered here. Energy consumption is often used as a measure of environmental performance, and is also a cost driver. Thus energy was modeled in detail in prior sections and detailed further in Appendix B. Energy consumption is calculated to be 915, 25, 491, and 148 MJ for the annealing, milling, hardening, and tempering processes respectively. Thus, a total of 1579 MJ of energy is consumed in-house to produce the component from the stock material. A sensitivity analysis on the milling energy equations can be seen in Figure 4.21, the analysis is performed to show how altering the process parameters of the previous UMP influence the energy consumption in the subsequent UMP. Reducing the annealing cooling time causes the component to become harder and thus the milling energy increases as shown in the figure.

Furthermore, because the material condition of the steel is unknown, the annealing process is required prior to milling. This annealing step would be possibly if received in proper condition and annealing would result in excess energy consumption. Thus, collaboration with suppliers to provide materials in the proper, or otherwise known, state will eliminate redundant processes and mitigate excess energy consumption and associated environmental impacts (e.g. resource depletion and carbon emissions).

Table 4.5: Results

Aspect	**Evaluation Criteria**	**Unit**	**Results**
Economic	Operating Cost	Dollars	28.30
Environmental	Energy Consumption	Megajoules	1579
	Water Use	Liters	0.036
	GHG Emissions	Kilograms CO_2 eq.	0.304
	Total Waste	Kilograms	3.37
Social	Average Wage	Dollars per hour	18.97
	Lost Work Days	Number of days	0.00118

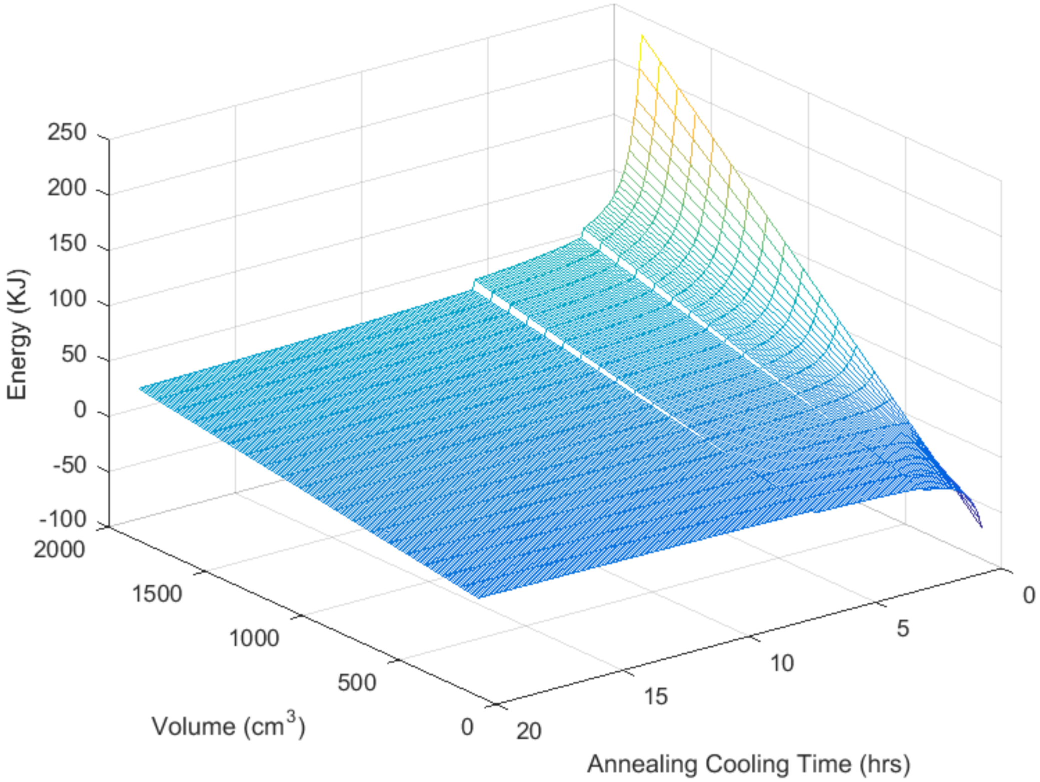


Figure 4.21: Sensitivity analysis on the milling energy as a function of the volume of material to remove and the annealing cooling time.

Based on the UMP energy models developed in the foregoing example, process optimization can be undertaken to minimize the energy use. The optimization would likely minimize annealing of the steel, as this process consumes significantly more energy than milling. A second important time based criterion considered is the cost of manufacturing, herein included energy, labor, and consumables. To fully capture process impact, equipment, tooling, and overhead would also need to be incorporated. Increasingly harder materials required higher power and torque to machine, thus as stronger and larger machines are required equipment costs increase. Furthermore, assuming the fracture toughness of the tooling remains constant, harder materials will cause tool life to decrease and increase tooling costs. Furthermore, the modeling concepts utilized enable predictive capabilities of component manufacturing for sustainability improving decision making capabilities within industry. Alternative component designs can be assessed to determine the best performing component. Or, improvement opportunities to the manufacturing facility can be identified using the calculations. These capabilities enable for industry decision makers to find the best use of funds.

4.6 Summary and Conclusions

Previous methods of workpiece modeling have focused on geometry to aid in UMP selection and MPF development, while previous UMP modeling efforts have addressed manufacturing system analysis. These two areas of work have not been integrated using the workpiece state (geometry and properties) as an information carrier between UMPs in an MPF.

Thus, an information modeling scheme was constructed to enable evaluation of workpiece-UMP interactions, UMP-UMP interactions, and workpiece-workpiece interactions. The focus of the work detailed herein has been on the first of these interaction. Workpiece-UMP interactions are the functional transformation of the workpiece due to the UMP. UMP-UMP interactions are the causal relationships that occur in MPFs. Workpiece-workpiece interactions are the joining of different workpieces and their function as a product system. Combining these different interactions into a unified framework (for example) is an attempt to answer the question posed above, “What inherent information is in a product and a manufacturing system that can aid in UMP selection, MPF development, and manufacturing system assessment?” This work revealed that specific process driven material properties are inherent to the workpiece and contribute to UMP impacts. Furthermore, the work captured and mapped several UMP evaluation criteria to process-related measures. Each criterion was affected by process time (a measure), as shown in Figure 4.10. Thus any workpiece property that affects the process time will affect the sustainability performance.

This work is limited to a UMP-workpiece interaction based on the UTS and YS, and a simple annealing, machining, hardening, tempering MPF. More UMP-workpiece interactions need to be identified and modeled, a UMP-UMP interaction database needs to be developed, for greater application of the composable information modeling framework. Furthermore, hardcoding UMP models, UMP-workpiece interactions, and MPFs in Mathworks MATLAB© can become an arduous as the MPFs under assessment become more complicated, implementation of the method within a software tool is needed to streamline assessments.

4.7 Acknowledgments

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4.8 Disclaimer

Certain products or services are identified in the paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products or services identified are necessarily the best available for the purpose.

4.9 Abbreviations

BLS	Bureau of Labor Statistics
CAM	Computer aided manufacturing
CAPP	Computer aided process planning
GD&T	Geometric dimensioning and tolerancing
JST	Japan Science and Technology Agency
MCDA	Multi criteria decision analysis
MPF	Manufacturing process flow

MRR	Material removal rate
NRC	National Research Council
UMP	Unit manufacturing process
UPLCI	Unit process life cycle inventory
UTS	Ultimate Tensile Strength
VMR	Volume of material removed

CHAPTER 5: CONCLUSION

Sustainable engineering and manufacturing is the design and creation of products with long-term benefits to our economy, society, and environment. Sustainable manufacturing is in the infancy of research and in the future may be guised under new names and will incorporate new concepts and ideas. In industry today, sustainability philosophy is guised under terms such as green engineering, environmentally responsible design and manufacturing, and social responsibility, among others. The future of company acceptance of sustainability philosophy is unknown, but will likely compete for priority of company investment with other corporate goals. Sustainability is interpreted with two opposing business philosophies. One interpretation of sustainable practices is as a cost required for business practices to meet required environmental and social regulations; this could be called an end-of-pipe solution, wherein sustainability is an afterthought. The second interpretation of sustainable practices is as a means to improve the economic, environmental, and social performance of business. Foster the use of design and manufacturing methods and tools for sustainability improvement, and not simply low-cost manufacturing, requires education and culture change for business decision makers and engineers (design, manufacturing, process, and operations engineers). The use of regulations to enforce sustainability is a method that helps ensure that a tragedy of the commons does not occur, for example by forcing sustainable practice to be less costly than the unsustainable alternative through incentives. Thus, research in both sustainable education and corporate culture are enablers to incorporating sustainable manufacturing assessment methods into business practices. Demonstrating the value of sustainable manufacturing assessment approaches is critical to acceptance into business practice.

5.1 Summary

The research reported herein was undertaken to advance sustainable manufacturing assessment in response to an increasing need for economic, environmental, and social performance improvement. Because these three sustainability aspects affect the standard of living for all people and since manufacturing activities account for a large percent of these impacts, methodologies are needed to support manufacturing decision making. Thus, the objective of the work reported was to provide a means for organizing and performing a unit manufacturing process (UMP) based sustainable manufacturing assessment.

Relevant terminology to UMP modeling and sustainable manufacturing assessments was defined by performing a literature review. The collected terminology can be used in communication of sustainable manufacturing assessments. A unified UMP assessment methodology was then developed through a review of past approaches reported in technical literature. This methodology can be used for assessment or improvement of manufacturing processes, products, or facilities. A UMP information modeling framework was also developed by analysis of a variety of UMP models for metals manufacturing, the models were developed in prior work and as part of this thesis research. Structuring information in a standard format is required for interchangeable UMP models to ensure that equivalent information is detailed in each. Finally, a framework for composing process models within a manufacturing process flow (MPF) by transferring workpiece information between UMP models was demonstrated using a mathematical example for a representative MPF to produce a steel component.

5.2 Conclusions

Learnings from this research support UMP model development and sustainability assessments of MPFs as follows: 1) It was found that many common terms used in sustainability and manufacturing assessment are similar and overlapping, from which terminology definitions were harmonized and then conceptually categorized. 2) Various methodologies for conducting sustainability assessments were found to have common themes, from which a unified, comprehensive methodology could be developed. 3) Investigation of causal relationships between UMPs for inspection processes revealed that UMP-workpiece, and UMP-UMP interactions could be further pursued. 4) Investigation into the structure of various UMP models revealed that information model composability could be accomplished with a focus on the UMP function in imparting workpiece transformation (e.g., workpiece geometry or property change). The following paragraphs detail the learnings of this thesis.

First, identifying and defining terminology in Chapter 2 lead to organizing the ideas within UMP characterization into different categories. These concepts included the scope of study, the boundaries of the study, the materials used for the UMP, the measurements undertaken to characterize a UMP, mathematical modeling of a UMP, and the flow of product through a UMP and MPF. Understanding these different concepts is the basis of communication of UMP characterization results. While terminology definitions will continue to be refined in the future, underlying concepts are not likely to vary. Thus, communication in business practices is enabled by common terminology both internally, for example between business units, managers and engineers, and externally, for example between suppliers and customers, and to shareholders and regulatory agencies.

Second, creating a unified methodology for assessing UMPs and MPFs in Chapter 3 lead to a better understanding of an overarching method for systematic improvement of manufacturing processes. Organizing and reviewing the previous methodologies allowed for a broader perspective to identify unstated assumptions within methods, e.g., many previous methods assume resources available to a team (and that a team exists for that matter) are identified prior to the assessment. Furthermore, the new methodology was designed with the intention of adaptivity, wherein each reviewed method could be recreated. Adaptivity is achieved by maintaining the Preparation, Execution, and Decision Phases in the framework and then selecting steps in each phase that match the application. Thus, a broader, more flexible methodology for UMP and MPF assessment and improvement emerged from the unique methods reviewed.

Third, modeling two inspection UMPs, magnetic particle inspection and penetrant inspection (Appendix C) fostered ideas of UMP composability. This understanding came from identifying the close similarities and differences between the two UMPs. Both UMPs performed equivalent functions, detecting surface defects of metal parts. Of the two UMPs, magnetic particle inspection is more robust at detecting defects because parts are not required to be clean, but parts are required to be ferromagnetic. Thus, penetrant inspection is used for non-ferromagnetic parts, but the process is less robust because it detects less defects and requires a clean component. In modeling and composability examination, UMP dependencies, while not immediately prominent, emerged and led to the thought that other UMP dependencies are identifiable, but not well recorded.

Fourth, creating an information modeling framework for UMP-workpiece interaction and modeling in Chapter 4 led to a better understanding of process functions and the data required to assess the sustainability of UMPs. The function of a UMP and the interaction with a workpiece needs to be reflected in any modeling that is performed, otherwise models can lead to misunderstandings and sub-optimal performance. The example steel component MPF developed for the chapter does not capture the detail of all processes in an actual MPF, nor are the models reflective of all process physics (e.g. vibrations). Thus the reducing UMP models would need to incorporate additional impacts, for example tool failure. Furthermore, the measurements performed on UMPs need to be standardized to ensure that UMPs and MPFs are comparable, while also being flexible to account for unique aspects of each UMP. In addition, physics-based workpiece models for material properties are needed for further UMP modeling composability efforts.

5.3 Contributions

The presented work focuses on characterizing unit manufacturing processes and manufacturing process flows for sustainable manufacturing assessment and has made several contributions to the research community.

Contribution 1: A categorized set of terminology and definitions for communicating and describing UMP based sustainable manufacturing assessments was established. The terminology enables clear communication of the concepts related to sustainable manufacturing assessments.

Contribution 2: A unified methodology for sustainability characterization of unit manufacturing processes and manufacturing process flows for sustainability improvement was created. The methodology enables an analyst to perform in-depth sustainability assessments of unit manufacturing processes, manufacturing process flows, and manufacturing systems to compare alternatives, identify improvement opportunities, and set benchmarks.

Contribution 3: An information modeling framework for UMP and workpiece characterization was created which provides a theoretical background for modeling and measuring UMPs. The framework enables composing UMP models using workpiece properties derived from the transformation to the workpiece caused by the UMP, thus also enabling improved MPF models.

5.4 Opportunities for Future Research

There are several opportunities for future research that are direct result of this research. First, future work can expand and build upon the modeling approach developed for demonstrating composability in UMP modeling. The UMP energy models in Chapter 4 and Appendix C were developed based upon previous research in mechanics and thermodynamic theory. While the models in Chapter 4 were validated in previous research, they were not validated using experimental results in this work due to limited access to equipment. Validation by empirical analysis would benefit future studies by improving accuracy and relevancy of the results. Second, further investigation into composing UMP models is needed for MPF assessment, the information modeling framework presented is currently limited to *ad hoc* solutions and does not provide a complete method for composable UMP modeling investigation.

Opportunity 1: The modeling approach demonstrated in Chapter 4 is limited to prediction of energy use for simple process flows, and is not capable of process parameter modification for the optimization of energy use at the system level. Numerical or heuristic techniques could be undertaken to find optimal operating parameters. To perform optimization of even the simplified process flow, additional, more-detailed, mathematical models are needed which would penalize the objective function for not annealing the workpiece. Additional models could include a probability model for cutting tool failure and energy consumption models for lost energy as a result of tool failure, i.e., the invested energy within the workpiece and the tool itself.

Opportunity 2: The example MPF created in Chapter 4 is limited to application of differing steel compositions, and thus limits the ability to predict the manufactuirng energy requirements of different products. Also, the current hardenability model does not accurately predict the hardness of annealed SAE 4340 steel, and results in inaccurate energy consumption calculations for the subsequent milling UMP. Creating or utilizing a hardenability model that is more accurate and applicable to a broader range of steel compositions would benefit the energy prediction model. An alternative hardenability model was identified in Chapter 4, which was derived from first principles, as opposed to the empirical model implemented in the work here; thus it would be more accurate and cover a broader range of applications.

Opportunity 3: The identified composability analysis is limited to a simplified heat treating and milling MPF, since the example investigation identified workpiece information transfer between these two UMPs. Investigating additional composable modeling opportunities between different UMPs and identifying different composability approaches would enable prediction of energy consumption and other sustainability performance criteria to enhance the capabilities of future engineering analysis tools. Other information transfers between UMPs that modify workpiece geometry or properties could be investigated, e.g., material structure-property relationships can be utilized.

5.5 Last Remarks

The 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 into digital MPFs will enable advancement of computer-aided manufacturing (CAM) and improvement of methods for manufacturing assessment. Composability modeling links multiple models together by sharing common variables, thus more common variables need to be identified in UMP modeling. Sustainable manufacturing can move forward in a multitude of ways, the methods presented herein can enable more detailed and accurate scrutiny of manufacturing processes and process flows, namely the economic, environmental, and social impacts of manufacturing activities. Incremental improvements can be made to manufacturing activities in American businesses, and as adoption of UMP-based assessment methods and tools spreads throughout businesses a more sustainable future can be realized.

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APPENDIX A: (FOR MANUSCRIPT 3): IDEF0 UMP MODELING DIAGRAMS

IDEF0 depictions of unit manufacturing process (UMP) models. Figure A.1 shows groups the inflows and outflows of the UMP similar to Figure 4.1. Figure A.2 is a breakdown of Figure A.1 into the different metric calculations, wherein each outflow shown in Figure A.1 has a corresponding representative box in Figure A.2 Figure A.3 shows different methods for operating cost calculations. Figure A.4 shows different methods for water use calculations. Figure A.5 shows different methods for waste generation calculations. Figure A.6 shows different methods for energy calculations. Figure A.7 shows the conversion of energy to GHG emissions. UMPs can also be represented using activity models, that would show the different sub-processes, sub-systems, equipment necessary for the process; but note not all of these resources are structured in an in-out flow concept.

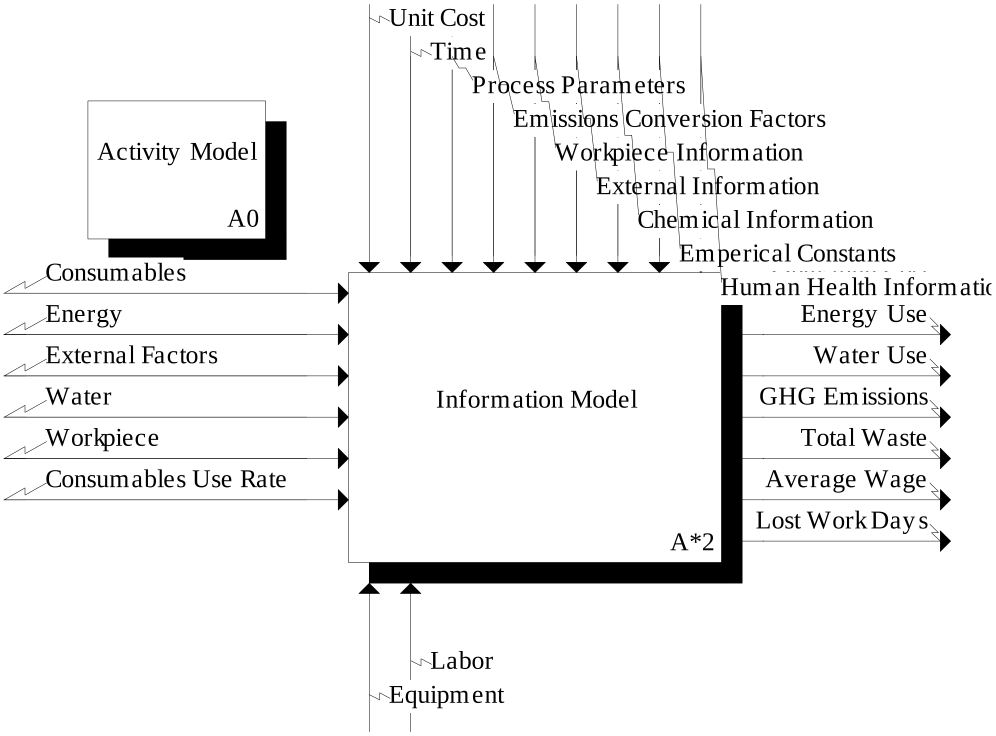

Figure A.1: Top UMP models, shows flow groups.

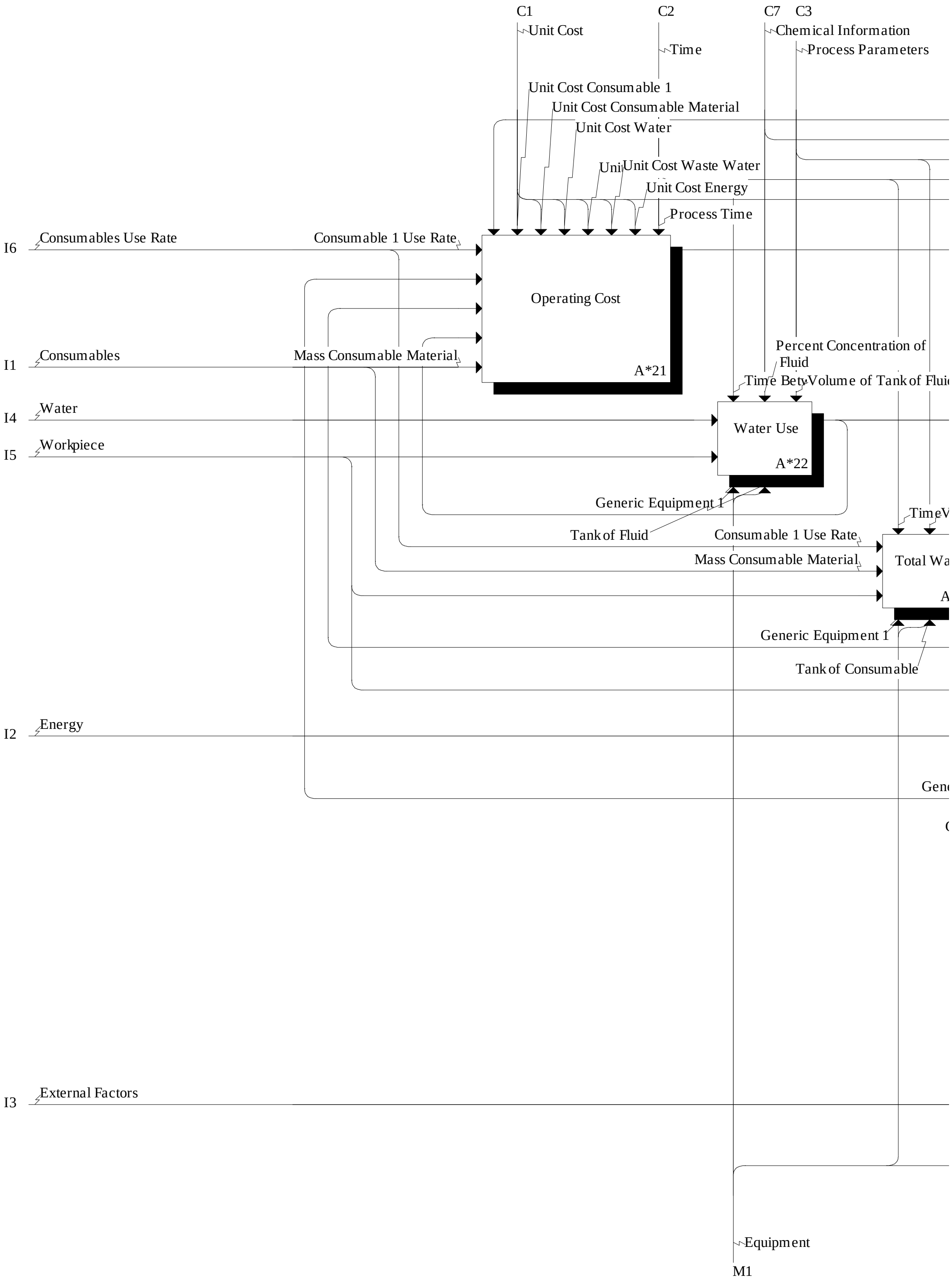

Figure A.2: Metric Calculations showing input and output flows

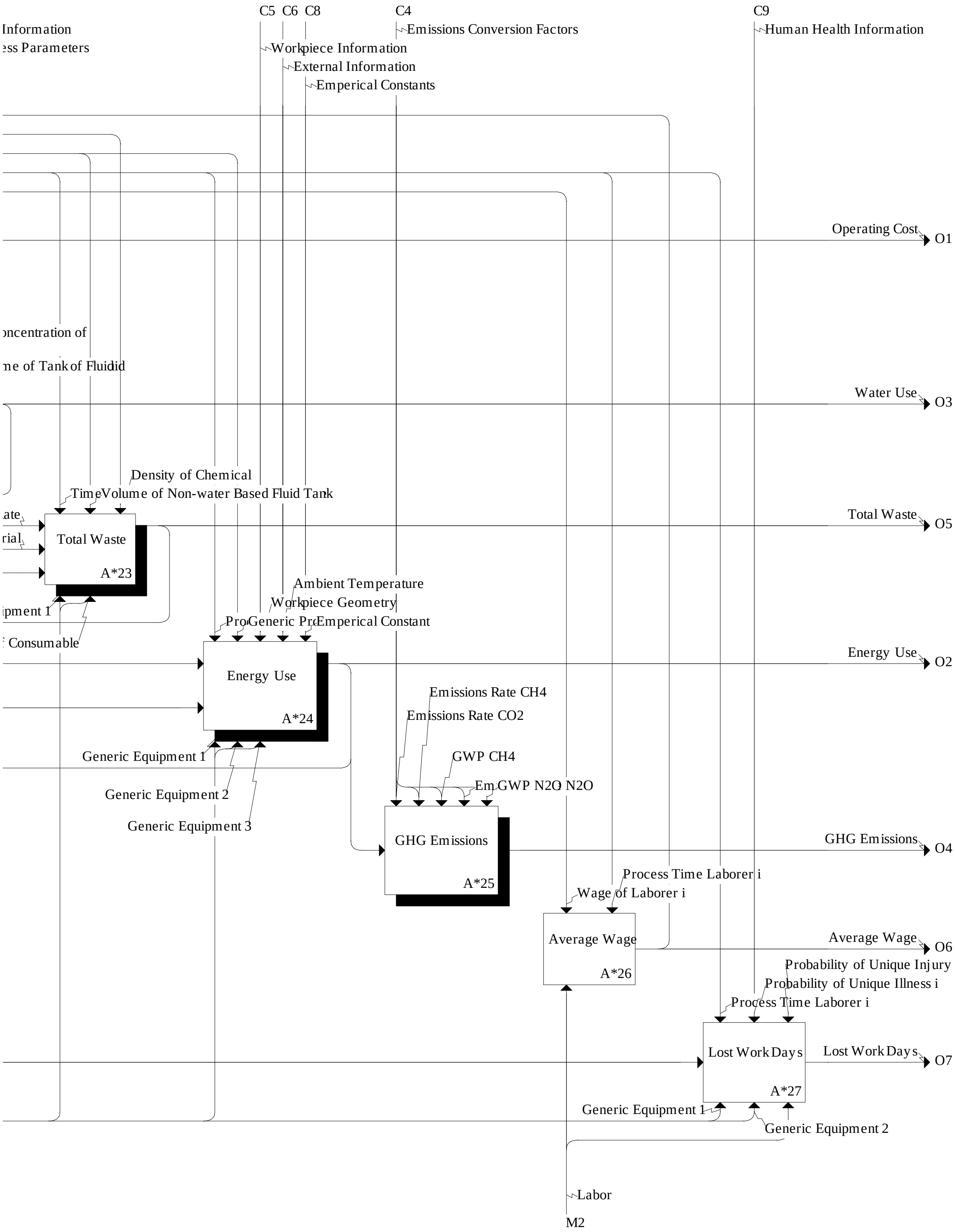

Figure A.2 (Continued): Metric Calculations showing input and output flows

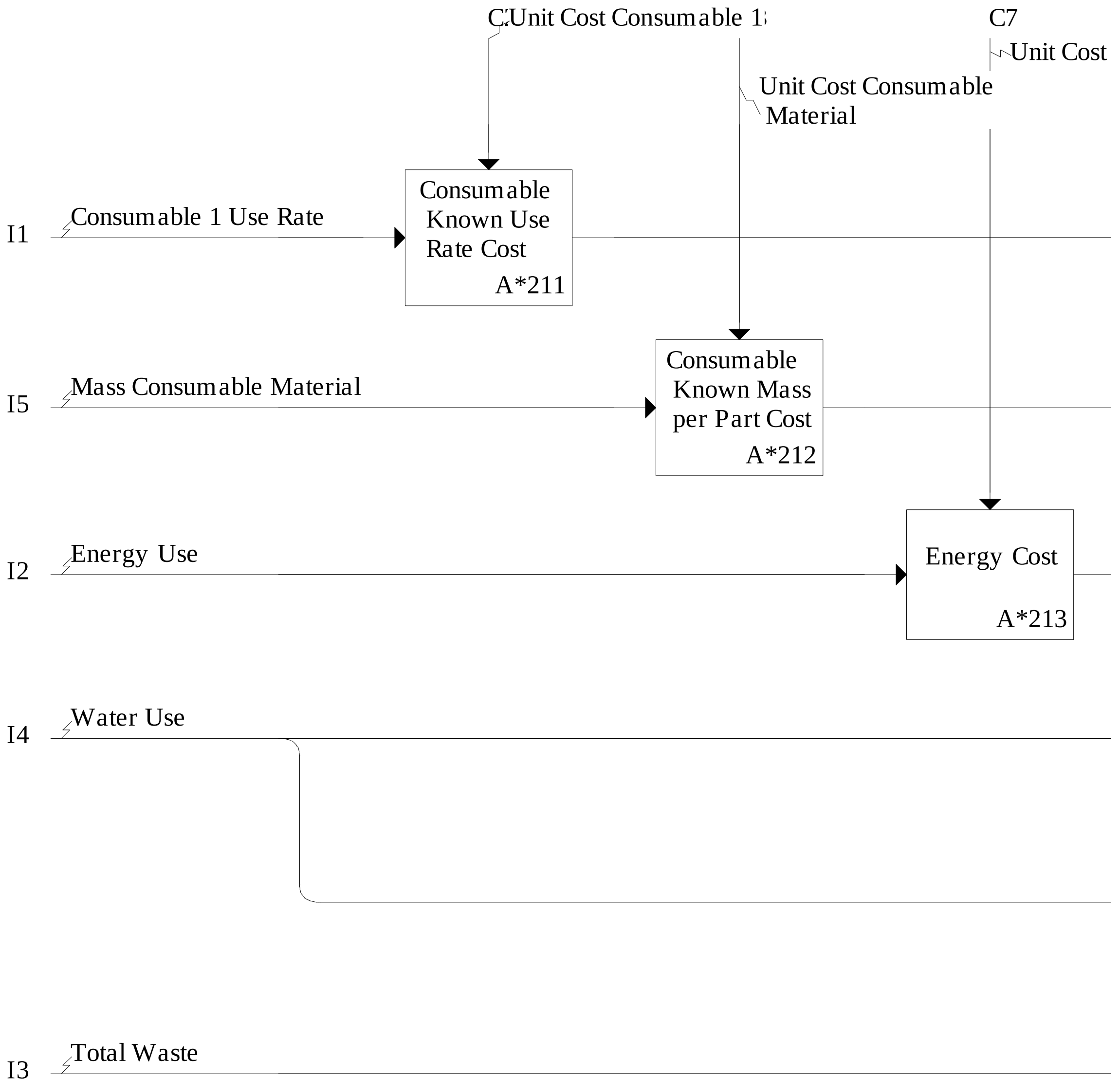

Figure A.3: Operating cost metric calculations

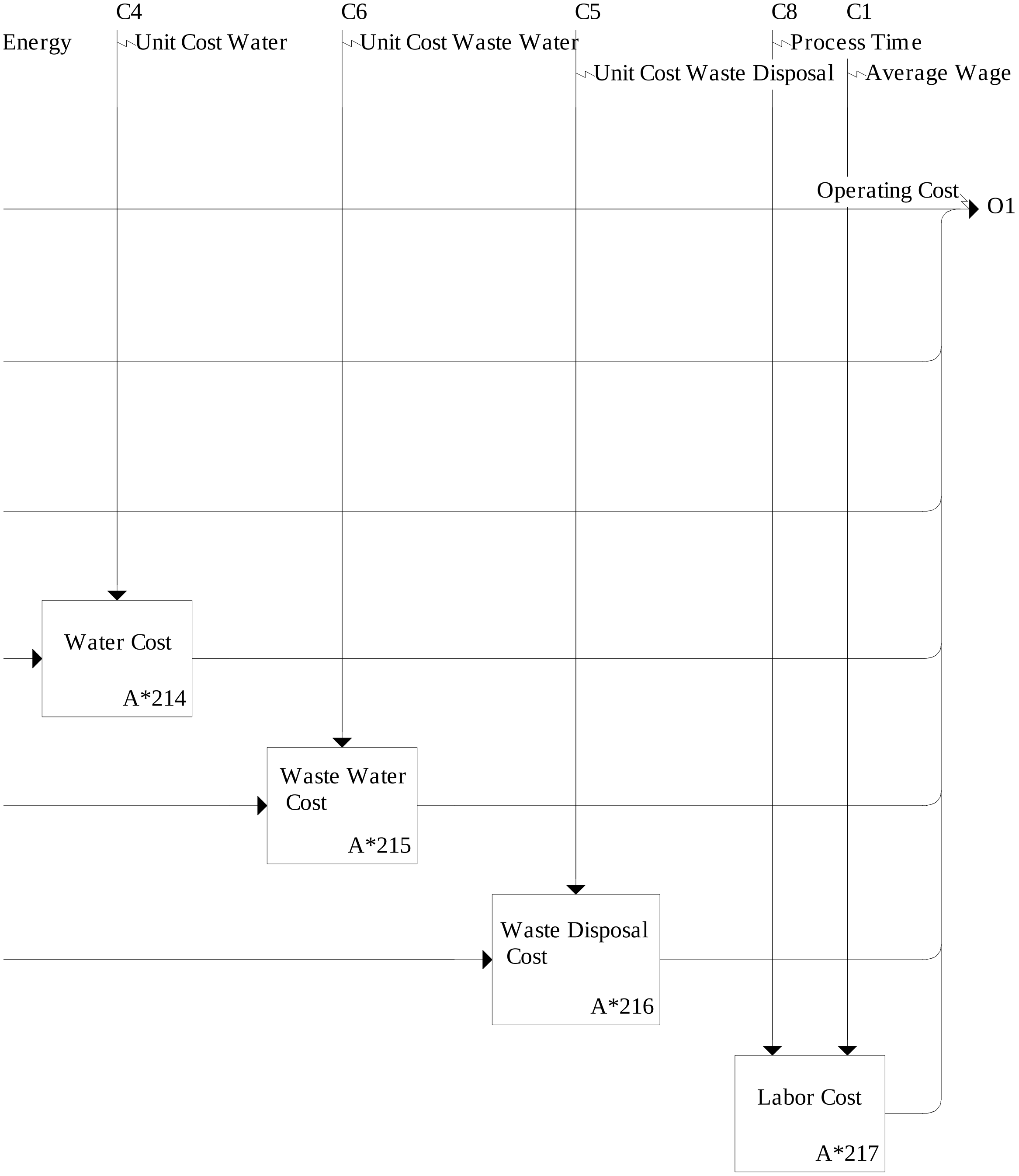

Figure A.3 (Continued): Operating cost metric calculations

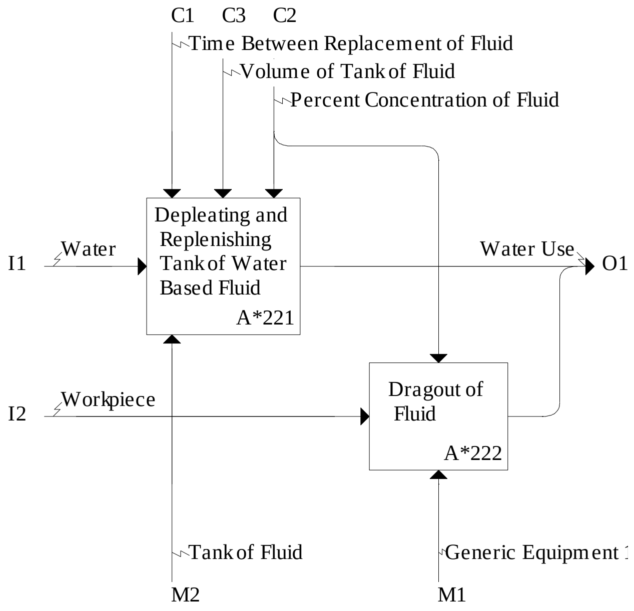

Figure A.4: Water use metric calculations

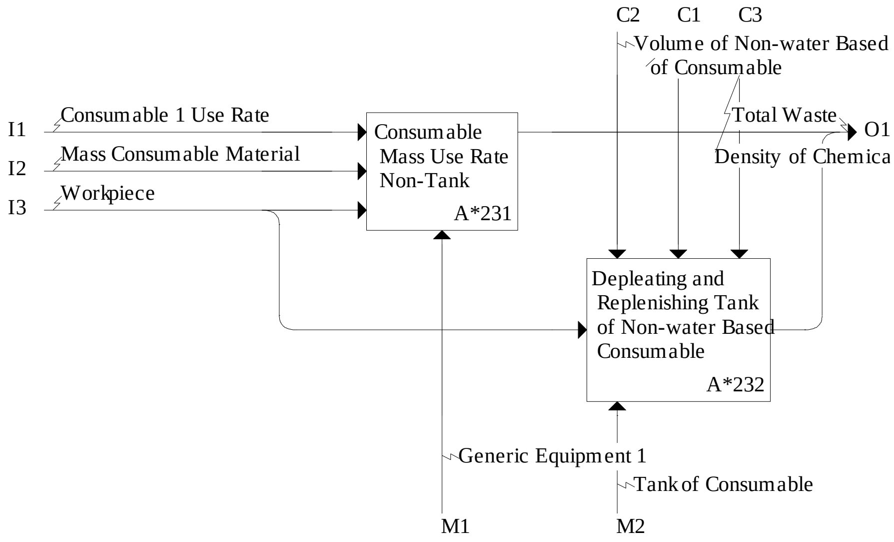

Figure A.5: Total waste metric calculations

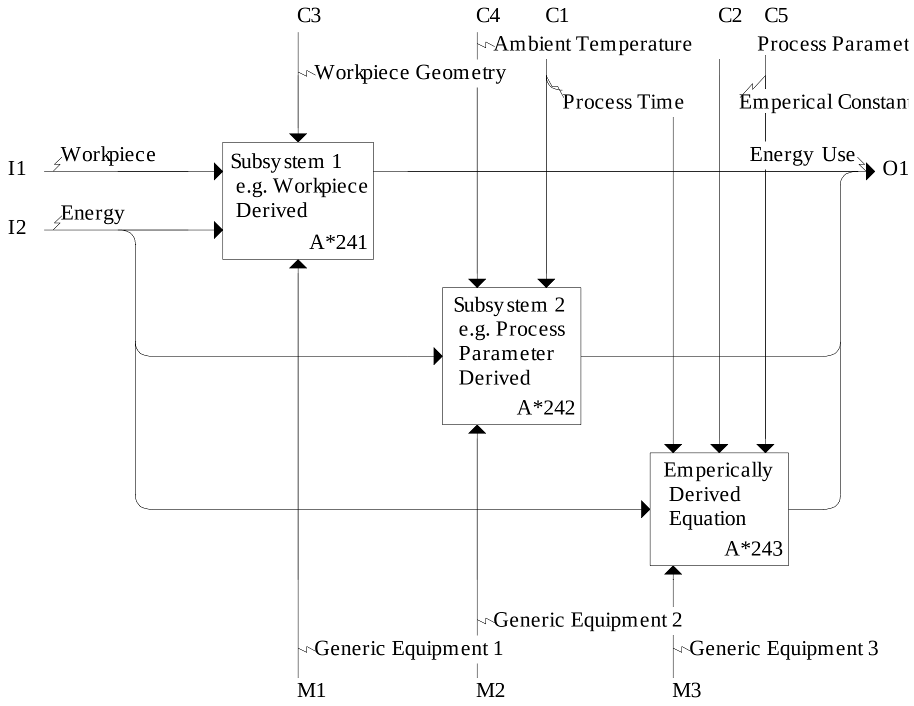

Figure A.6: Energy use metric calculations

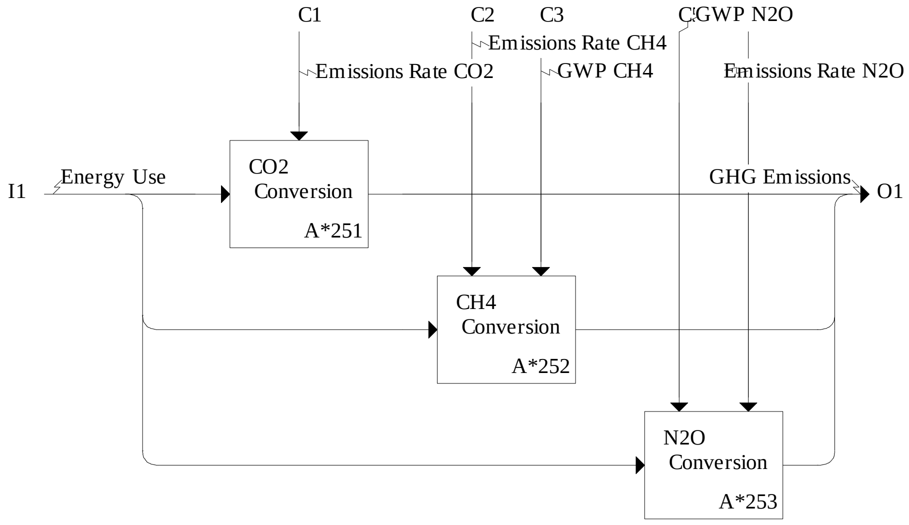

Figure A.7: GHG emissions metric calculations

APPENDIX B: (FOR MANUSCRIPT 3): EXCERPT OF MATLAB CODE

B.1. Main Code

```
clear all
format compact

%input variables


%Timer
tic;

%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Initial Workpiece State
%WP_Hard = ;%Hardness
WP_Vol_Int = 0.0009218;% m3 Initial Volume
WP_Den = 7850;% kg/m3 Density Steel
WP_Mass_Int = WP_Vol_Int*WP_Den; %kg
WP_Thick = 2; %in thickness in inches used to calculate oven times

%weight percent steel composition; 4340; assumed highest percent
%composition
St_C = 0.43;
St_Si = 0.3;
St_Mn = 0.8;
St_Ni = 2;
St_Cr = 0.9;
St_Mo = 0.3;
St_V = 0;
St_Cu = 0;
ST_Fe= 95.27;


%%%%%%%%%%%%%%%%%%%%%%%%%%
%Recrystalization Annealing


%Input paramters
t_Anneal = 60*60*WP_Thick; % sec Annealing Process Time; [ASM handbook
on Heat treating, pg.282], Rule of thumb for full austenization is
given as 1hr. per inch of part thickness. For model improvement,
consider adding this as a rate parameter that could be adjusted.
```

```
Temp_Oven = 840; % C Oven Temperature
Temp_Room = 28;% C Room Temperature
Temp_DownFlue = 30;% C Temperature flue downstream (outdoor
temperature)
Temp_Wall = 40;% C Furnace wall temperature

%Call energy function

Energy_Anneal =
Energy_Oven(t_Anneal,Temp_Oven,Temp_Room,Temp_DownFlue,WP_Mass_Int) %En
ergy given in megajoules (MJ)
disp('MJ');


%%%%%%%%%%%%%%%%%%%%%%%%%%

%Workpiece state 2


%Input parameters

Cooling_Rate = 8.5/(60*60); %C/sec cooling rate for annealing (8.5 deg.
C/hour); [pg. 293, ASM heat treat guide]
t_Cooling = 16.5*60*60; %sec cooling time for annealing (16.5 hour);
[pg. 293, ASM heat treat guide]
T = Temp_Oven;

%Call hardness function

%WP_Hv

=HT_CL_Hard(St_C,St_Si,St_Mn,St_Ni,St_Cr,St_Mo,St_V,Cooling_Rate,T,t_Co

oling);  %Vickers  Hardness,    [Maynier,  Dollet,  and  Bastien  1978],

[Trzaska, Jegietto, and Dobzanski 2009]

WP_Hv = 240;   %Vickers Hardness    [ASM Handbook] used in place for
the hardness model because it was inaccurate
WP_UTS = -99.8+3.734*WP_Hv; %MPa,       [Pavlina and Van Tyne 2008]
WP_UTS = WP_UTS*10^6; %Pa


%WP_Hv should be near 223 HB (from ASM handbook) which is near 240-250

HV.

%This gives me 97.




%%%%%%%%%%%%%%%%%%%%%%%%%%

%Reducing (Chipping)


%Input Parameters

VMR = 0.0004289;% m3 Volume of material removed
```

```
MRR = 0.63*(0.0254^3)*(1/60);% m3/sec material removal rate (0.63
in3/min for 1/2in endmill and 1.47 in3/min for 1in endmill) [Polgar
1995]
VelCut = 106.68/60; % mpm meters per minute
double check
ThetaMax = 360;

%call energy function

[Energy_Cut,t_Reduce] =
Cutting_Energy_Incremental(WP_UTS,VMR,MRR,VelCut,ThetaMax); %N [Groover
2015]


% t_Reduce;


%Scale energy up to whole mill

Percent_Cut_Energy = .15;% percent of energy used for machining,
[gutowski]
Energy_Mill = Energy_Cut/(Percent_Cut_Energy*10^6)  %MJ
disp('MJ');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Workpiece State 3


WP_Vol_final = WP_Vol_Int - VMR;% m3 workpiece final volume
WP_Mass_Final = WP_Vol_final*WP_Den; % kg
WP_Thick = 1;%in used to calculate oven times

%if the next step were to anneal
%if you were anealing the part again instead of hardening, then the
entire
%part does not have to austenized and could be just the surface
hardness
%possibly add a model for calculating the surface hardness thickness



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Through hardening


%Input parameters
t_Hard =60*60*WP_Thick; % sec time through hardening; [ASM Handbook on
Heat Treating pg.282] for calculation 1hr*#in thick
Temp_Oven = 900;% C Oven Temperature
```

```
Temp_Room = 28;% C Room Temperature
Temp_DownFlue = 30;% C Temperature flue downstream

%call function

Energy_Hard =
Energy_Oven(t_Hard,Temp_Oven,Temp_Room,Temp_DownFlue,WP_Mass_Final) %MJ
disp('MJ');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Workpiece State 4


%Input parameters

Temp_Quench = 30; %temperature of the quenchant, choose water, oil,
etc.
% Cooling_Rate = 8.5/(60*60); %C/sec cooling rate for annealing;

t_Cooling = 10; %Sec cooling time for annealing; look up cooling rate
Cooling_Rate = (Temp_Oven-Temp_Quench)/t_Cooling; %C/sec cooling rate
calculation
T = Temp_Oven;

%Call hardness function

WP_Hv =
HT_CL_Hard(St_C,St_Si,St_Mn,St_Ni,St_Cr,St_Mo,St_V,Cooling_Rate,T,t_Coo
ling);  %Victers Hardness, [Maynier, Dollet, and Bastien 1978],
[Trzaska, Jegietto, and Dobzanski 2009]
WP_UTS = -99.8+3.734*WP_Hv; %MPa,       [Pavlina and Van Tyne 2008]




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Workpiece Final State


% % [Bag et al. 1999] Inter Critical Temperature from WP_Yield Strength

% %Input parameters

% WP_Hard_Fin = 282;% victers diamond pyrmid, final hardness

%

% %Call Stength function

% WP_YS_Fin = -90.7+2.876*WP_Hard_Fin;

%

% %mean free path martensite

% MFPM = 10^((2.8565-log10(WP_YS_Fin))/-0.25441);
```

```
%
% %volume fraction of martensite
% VFM = ((1.03-MFPM)/0.045)^(1/-2.87); %imaginary
%
% %intercritical temperature
% Temp_IC = log(VFM/0.0052)/0.0058

%[Tavares, Pedroza, Teodosio, Gurova 1999]
WP_YS_Fin = 300; %MPa

Temp_IC = (551-WP_YS_Fin)/(0.454); %C



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Recovery annealing

%Input parameters
t_Recover = 60*60*.5;% sec time through hardening
Temp_Oven = Temp_IC; % C Oven Temperature
Temp_Room = 28;% C Room Temperature
Temp_DownFlue = 30;% C Temperature flue downstream

%Call energy function
Energy_Recover =
Energy_Oven(t_Recover,Temp_Oven,Temp_Room,Temp_DownFlue,WP_Mass_Final)
%MJ
disp('MJ');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Final Output
Energy_Total = Energy_Anneal + Energy_Mill + Energy_Hard +
Energy_Recover %MJ
disp('MJ');

%timer
toc
```

B.2. Oven Energy Model

```
function [ Energy_Total ] =
Energy_Oven( Time_Process,Temp_Oven,Temp_Room,Temp_Flue,WP_Mass )
%UNTITLED2 Summary of this function goes here

% Energy Performance assesment of Furnaces

% National Certification Examination for Energy Managers and Energy

% Auditors


% Energy Management Series

% Process Furnaces, Dryers, and Kilns

% Department of Mines and Resources Canada




%Input Parameters

Coefficient_OvenWall = 0.36 ; %W/(m*K)      [From Morgan Thermal
Ceramics]
Area_WallSurface = 8; %m2
Thickness_Wall = 0.1524 ; %m
WP_Coefficient_HeatCapacity = 502; % J/(kg*K)
%Mass_Oven_Air = ;

Coefficient_FlueGasSpecificHeat = 1004.16; %J/(kg*K)           NW
Natural 0.044lb/ft3
Density_FlueGas = 1.23; %kg/m3
FlowRate_FlueGas = 235*0.028316846592; %m3/min;      conversion from
ft3 to m3
Percent_OxygenFlueGas = 8; % %
Mass_Stoichometric_Air = 11*0.0283168*1.225/(1*0.023168*0.66); %kg/kg
CH4
Mass_CH4 = 1 ; %kg/kf CH4
% Enthalpy_CH4 = 45000;% kJ/kg Enthalpy of Combustion Natural Gas

% Percent_Uncombust = 3;% % Percent Uncombusted Combustibles

%FlueGas_AvailableHeat = 0.75;% user defined efficiency


%Conversion

Temp_Oven = Temp_Oven + 273;
Temp_Flue = Temp_Flue + 273;
Temp_Room = Temp_Room + 273;
% Temp_Wall = Temp_Wall + 273;




% % calculation of Wall temperature

% Boltzman = 5.6703*10^-8; %W/m2K4

% Emissivity = .59; %of stainless steel
```

```
%Finding roots for the convective and radiative heat transfer. Assumed
that
%the heat transfer for both are equal, thus the root is multiplied by 2
%for a solution. The first root finder is for the wall temperature.
Root
%outputs will give two imaginary and two real roots.  This is used to
%verify that a real value is used. The second finds the heat transfer.
Both
%roots are checked to find the combination of real roots in the for
loop.

%Inputs to radiation and convection.
Boltzman = 5.6703*10^-8;    %W/m2K4
Emissivity = .59;           %of stainless steel
Coefficient_Air = 300.19*1000 ;  %h, J/kg

%Wall Temperature
ra = Emissivity*Boltzman/Coefficient_Air;
rb = 0;
rc = 0;
rd = -1;
re = (-Emissivity*Boltzman/Coefficient_Air)*(Temp_Room^4)+Temp_Room;

rp = [ra rb rc rd re];
rr = roots(rp);

%Heat Transfer
rf = 1;
rg = -4*Temp_Room/(Coefficient_Air*Area_WallSurface);
rh = 6*(Temp_Room^2)/(Coefficient_Air*Area_WallSurface);
ri = (-
4*(Temp_Room^3)/(Coefficient_Air*Area_WallSurface)+1/(Emissivity*Boltzm
an*Area_WallSurface));
rj = 0;

rq = [rf rg rh ri rj];
rs = roots(rq);

%Selects the real root.
for rz = 1:4
    rx = isreal(rr(rz));
    ry = isreal(rs(rz));
```

```
    if rx == 1 & ry == 1
        if rs(rz) < 0
            rs(rz) = -rs(rz);
        end
        Heat_Rad_Conv = 2*rs(rz); %J/sec
    else
        Heat_Rad_Conv = 0; %J/sec
    end
end




%Calculations


Excess_Oxygen = (Percent_OxygenFlueGas/(21-
Percent_OxygenFlueGas))*100;   %percent


Mass_Air =
Mass_Stoichometric_Air*(1+(Excess_Oxygen/100));                 %kg


Time_MassFlow =
(Mass_Air+Mass_CH4)/(Density_FlueGas*(FlowRate_FlueGas)/60); %sec


Heat_FlueGasLoss = (Temp_Oven-Temp_Flue)*(Mass_Air+Mass_CH4)...

*Coefficient_FlueGasSpecificHeat*(1/Time_MassFlow);%...
                    %*(1-
FlueGas_AvailableHeat);                                  %J/sec

Heat_OvenWallLoss = Coefficient_OvenWall*Area_WallSurface...
                    *(Temp_Oven-
Temp_Room)/Thickness_Wall;              %J/sec


Energy_Part_Carryoff = WP_Coefficient_HeatCapacity*WP_Mass...
                      *(Temp_Oven-Temp_Room);                  %J


Energy_Total = (((Heat_OvenWallLoss+Heat_FlueGasLoss+Heat_Rad_Conv)...
                *Time_Process)+Energy_Part_Carryoff)...
                /(1000*1000);                                %MJ


%Mass_CH4Burned = (Energy_Total/Percent_Uncombust)*(1/Enthalpy_CH4)


end
```

B.3. Milling Energy Model

```
function [ Energy_Cut,t_Reduce ] =
Cutting_Energy_Incremental( WP_UTS,VMR,MRR,VelCut,ThetaMax)
%Integrate Cutting Forces to determine the total cutting force for a
given
%volume, MMR, UTS, and Cutting Velocity
%   [Groover 2015]



%Tool input parameters
Nt = 2;              %number of teeth
Dia_Tool = 1*0.0254; %m tool diameter in meters used from assumption of
polgar
Apt = Dia_Tool*.02/Nt; %m/tooth
%Ap_Rev = Apt*Nt; %m/rev advance per revolution
Helical_Angle = 20; %degrees; inclination angle of the cutting tool;
try 20-40; page 14
http://www.guhring.com/documents/catalog/endmills/endmills.pdf
alpha = 40; %degrees; Rake_Angle
r = .5; %unitless; chip thickness ratio
% to = 0.000127; %m depth of cut


%Machine input parameters
VelCut = VelCut*60; %mpm meters per minute
RPM = VelCut/(3.141*Dia_Tool); %rev/min



%Calculate number of revolutions to integrate for the machining
operation
Vol_Rev = MRR/(RPM/60); %m3/rev volume removed per revolution.
Revs = VMR/Vol_Rev; %total number of revolutions the tool will take



%calculate the constants for force calculation
FeedPMin = Apt*RPM*Nt;   %feed per minute (meters/min)
Timerev = 1/(RPM/60); %sec/rev time of revolution in seconds

%depth of cut to integrate over
zmax = .5*Dia_Tool; % depth of cut meters
```

```
%Step size for z integration
zstep = (2*pi()*Dia_Tool*.5)/(360*tand(Helical_Angle));

%have to calculate number of steps for for loop to work; could use
while
%loop as alternative
zstepnumber = zmax/zstep;

%step size for angular integration
thetastep = (zstep*360*tand(Helical_Angle))/(2*pi()*Dia_Tool*.5);

%       a trigger for identifying the exit roation angle
bool = 0;
thetaExit = 360;

% When stp = 1 Elapsed time is 26128.610153 seconds.
% When stp = 100 Elapsed time is 405.800479 seconds.
%         M = zeros(1:num);
M = 0;
L = 0;
ctr = 1;

        %declare matricies so that they can be filled in later.
         J = zeros(round(ThetaMax),round(zstepnumber));
         K = zeros(round(ThetaMax),round(zstepnumber));
         JA  = zeros(round(ThetaMax),round(zstepnumber));
         JK  = zeros(round(ThetaMax),round(zstepnumber));

        %Integrate for the cutter angle
        for i=1:thetastep:ThetaMax %i is the angle of the cutter

                %Tricks code into integrating for the rotation of two
                %tooth cutting mill. Would have to change for more or
less
%                 %teeth.
                theta = i;
                thetaNorm = (theta/360)-(floor(theta/360));
                if thetaNorm > 0.5;
                    thetaNorm = thetaNorm-0.5;
                elseif thetaNorm == 0;
                    thetaNorm = 1;
                end
                theta = 360*thetaNorm;

%                 boolexit = 0; %for exiting if no cutters are engaged.
                row = 1; %for tracking the row
```

```
                %Integrate for the z direction
                for zint = 0:1:zstepnumber

                    %identifies where the current zstep is in the
rotation
                    thetaInt = theta - thetastep*(zint);

                    %if the z increment is not engaged yet then exit
the
                    %loop early
                    if thetaInt < theta
%                        boolexit = 1
                       break
                    end

                    %Instantious Cutting Force Equations for X and Y,
for a known UTS and
                            %spindle position
                            %Reducing (Chipping)

                            %avoid divide by zero in r calculation
                            if thetaInt == 180
                                thetaInt = thetaInt - 1;
                            elseif thetaInt == 360
                                thetaInt = thetaInt - 1;
                            end

                            %Chip Thickness calculation
                            to = Apt*sind(thetaInt); %m

                            % %calculate shear angle and friction angle
                            phi = atand(r*cosd(alpha)/(1-
r*sind(alpha)));
                            beta = 90+alpha-2*phi;

                            %calculate shear zone area, dependent on
cutter orientation and engagement
                            % As = to*width/sin(phi); %m^2
                            ShearWidthMax =
zmax/cosd(Helical_Angle); %maximum width of shear
                            % hypotenuse of shear triangle=Arc length
/ sin(helical angle of cutter)
                            Width =
(2*pi()*(Dia_Tool/2)*thetastep/360)/sind(Helical_Angle); %current width
of shear

                            WidthCheck =
(2*pi()*(Dia_Tool/2)*theta/360)/sind(Helical_Angle); %used to track
entire cutter position relative to chip height

                            if thetaInt > thetaExit %if the incremental
cutter has exited the engagement arc, then zero Area
```

```
%                                    Width = (2*pi()*(Dia_Tool/2)*(360-
theta)/360)/sind(Helical_Angle); %current width of shear
%                                 As = to*Width/sind(phi);
                                As = 0;
                            elseif WidthCheck > ShearWidthMax %used to
determine the exiting angle
                                As = to*Width/sind(phi);
                                if bool == 0; %to triger the exit of
the cutter
                                    bool = 1;
                                    thetaExit = 360-thetaInt; %is exit
correct? 360? if tooth 1 vs 2?
                                end
                            else
                                As = to*Width/sind(phi);
                            end



                            %calculate cutting force with known UTS
(which corresponds to shear stress
                            %of the material)
                            dFc = WP_UTS*As*cosd(beta-
alpha)/(sind(phi)*cosd(phi+beta-alpha)); %Newtons
                            dFt = WP_UTS*As*sind(beta-
alpha)/(sind(phi)*cosd(phi+beta-alpha)); %Newtons


                            %Add source
                            dFx = -dFc*cosd(thetaInt)-
dFt*sind(thetaInt); %Newtons
                            dFy = dFc*sind(thetaInt)-
dFt*cosd(thetaInt); %Newtons



                    %cutting forces in X
                    J(ctr,row) =
Nt*thetastep*(FeedPMin/60)*Timerev*dFx;  %Newtons*m/rev = J/rev
                    M = M + J(ctr,row);
                    %cutting forces in Y
                    K(ctr,row) =
Nt*thetastep*(FeedPMin/60)*Timerev*dFy; %Newtons*m/rev = J/rev
                    L = L + K(ctr,row);
                    %matrix for shear area
                    JA(ctr,row) = As;
                    %matrix for sum of forces in X and Y, used for
graphing
                    JK(ctr,row) = J(ctr,row)+K(ctr,row);

                    row = row+1;
                end
```

```
                ctr = ctr + 1;

%                 %Wait Bar

%                 perc = i/num;

%                 waitbar(i/num,Wt_Br,sprintf('%d%% Waiting',perc))

%

%             end
        end

JS2 = sum(J,2);
KS2 = sum(K,2);
JKS2 = sum(JK,2);
JAS2 = sum(JA,2);

figure
subplot(2,1,1)
plot(JS2); hold on;
plot(KS2); hold on;
plot(JKS2)
title('Joules per Revolution')
legend('X','Y','X+Y')
subplot(2,1,2)
% plot(JA1,'color','y'); hold on;

plot(JAS2)
title('Shear Area')
legend('Area')
%legend('X','Y','X+Y','Area1','Area2')



% % MaX = max(J)

% MaY = max(K)

% MaXY = max(JK)

%

% MiX = min(J)

% MiY = min(K)

% MiXY = min(JK)


%multiply the

Energy_X = M*Revs;
Energy_Y = L*Revs;


Energy_Cut = (Energy_X+Energy_Y);  %Joules
```

```
t_Reduce = Revs*Timerev*(360/ThetaMax);

% close(Wt_Br);
end
```

B.4. Steel Hardening Model

```
function [ Hardness_Vickers ] =
HT_CL_Hard( St_C,St_Si,St_Mn,St_Ni,St_Cr,St_Mo,St_V,Vr,T,t )
%The Creusot-Loire System
%[Maynier, Dollet, and Bastien 1978], [Trzaska, Jegietto, and Dobzanski
2009]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Creusot-Loire System

%The function is somehow broken, the pearlite is 97 when it should be
240

%input parameters
%T = ;% deg K
n = 2.3;% napierian lograithm of 10
R = 8.3144621; % J/(mol*K) gas constant
H = 460.55*10^3;% J/mol
%t = ;% time
to = 60*60;% unit of time = 1 hr

%some parameter
Pa = ((1/T)-(n*R/H)*(log(t/to)))^-1;

%Cooling Velocities in logrithms C/hr
Log_Vm = 9.81-
(4.62*St_C+1.05*St_Mn+0.5*St_Cr+0.66*St_Mo+0.54*St_Ni+0.00183*Pa);
Log_Vm90 = 8.76-
(4.04*St_C+0.96*St_Mn+0.58*St_Cr+0.97*St_Mo+0.49*St_Ni+0.001*Pa);
Log_Vm50 = 8.50-
(4.13*St_C+0.86*St_Mn+0.41*St_Cr+0.94*St_Mo+0.57*St_Ni+0.0012*Pa);
Log_Vb = 10.17-
(3.80*St_C+1.07*St_Mn+0.57*St_Cr+1.58*St_Mo+0.70*St_Ni+0.0032*Pa);
```

```
Log_Vb90 = 10.55-
(3.65*St_C+1.08*St_Mn+0.61*St_Cr+1.49*St_Mo+0.77*St_Ni+0.0032*Pa);
Log_Vb50 = 8.74-
(2.23*St_C+0.86*St_Mn+0.59*St_Cr+1.60*St_Mo+0.56*St_Ni+0.0032*Pa);
Log_Vfp = 6.36-
(0.43*St_C+0.49*St_Mn+0.26*St_Cr+0.38*St_Mo+(2*St_Mo^.5)+0.78*St_Ni+0.0
019*Pa);
Log_Vfp90 = 7.51-
(1.38*St_C+0.35*St_Mn+0.11*St_Cr+2.31*St_Mo+0.93*St_Ni+0.0033*Pa);

%remove logrithims & convert to C/sec
Vm = (10^Log_Vm)/(60*60);
Vm90 = (10^Log_Vm90)/(60*60);
Vm50 = (10^Log_Vm50)/(60*60);
Vb = (10^Log_Vb)/(60*60);
Vb90 = (10^Log_Vb90)/(60*60);
Vb50 = (10^Log_Vb50)/(60*60);
Vfp = (10^Log_Vfp)/(60*60);
Vfp90 = (10^Log_Vfp90)/(60*60);

%solve for parameters from cooling rate. The cooling rate is checked
%against the critical cooling rate values and then the percent
composition
%is interpolated.


if Vr>=Vm %incorrectly comparing time to cooling rate??? These should
both be cooling rates.
    Xm = 100;
    Xb = 0;
    Xf = 0;
    Xp = 0;
elseif Vr>=Vm90
    Xm = (Vr-Vm90)*(100-90)*(1/(Vm-Vm90))+90;
    Xb = 100-Xm;
    Xf = 0;
    Xp = 0;
elseif Vr>=Vm50
    Xm = (Vr-Vm50)*(90-50)*(1/(Vm90-Vm50))+50;
    Xb = 100-Xm;
    Xf = 0;
    Xp = 0;
elseif Vr>=Vb
    Xm = (Vr-Vb)*(50)*(1/(Vm50-Vb));
    Xb = 100-Xm;
    Xf = 0;
    Xp = 0;
elseif Vr>=Vb90
    Xm = 0;
    Xb = (Vr-Vb90)*(100-90)*(1/(Vb-Vb90))+90;
    Xf = 100-Xb;
```

```
    Xp = 0;
elseif Vr>=Vb50
    Xm = 0;
    Xb = (Vr-Vb50)*(90-50)*(1/(Vb90-Vb50))+50;
    Xf = 100-Xb;
    Xp = 0;
else

    Xm = 0;
    Xb = 0;
    Xf = 100;
    Xp = 0;
end


    Xm=Xm/100;
    Xb=Xb/100;
    Xf=Xf/100;
    Xp=Xp/100;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Hardness model


Hvm = 127+949*St_C+27*St_Si*11*St_Mn+8*St_Ni+16*St_Cr+21*log(Vr);

Hvb = -
323+185*St_C+330*St_Si+153*St_Mn+65*St_Ni+144*St_Cr+191*St_Mo+...
      (89+53*St_C-55*St_Si-22*St_Mn-10*St_Ni-20*St_Cr-
33*St_Mo)*log(Vr);

Hvfp = 42+223*St_C+53*St_Si+30*St_Mn+12.6*St_Ni+7*St_Cr+19*St_Mo+...
      (10-19*St_Si+4*St_Ni+8*St_Cr+130*St_V)*log(Vr);

Hardness_Vickers = Xm*Hvm+Xb*Hvb+(Xf+Xp)*Hvfp;

end
```

APPENDIX C: UNIT MANUFACTURING PROCESS MODELS FOR FERROMAGNETIC AND NON-FERROMAGNETIC ALLOY SURFACE INSPECTION METHODS

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APPENDIX C: UNIT MANUFACTURING PROCESS MODELS FOR FERROMAGNETIC AND NON-FERROMAGNETIC ALLOY SURFACE INSPECTION METHODS

C.1. Abstract

Industrial use of natural resources are increasing at an alarming rate. Engineering and decision support tools are needed for analyzing and curbing industrial consumption of resources. Further, assessment methods to measure and indicate continuous improvement are also needed. Modeling individual manufacturing processes facilitates the generation of quantifiable evidence that improvements are being made. Such a modeling approach is developed and demonstrated in this paper to characterize sustainability performance of two metals inspection processes: magnetic particle inspection for ferromagnetic alloys and penetrant inspection for non-ferromagnetic alloys. Individual unit manufacturing process (UMP) models were developed by observing the inspection practices at an aircraft component manufacturer, and a mathematical basis for comparison with other inspection processes was identified. The paper further demonstrates the aggregation of performance metrics from all UMPs across a manufacturing process flow thus providing a basis for generating detailed sustainability performance assessments of manufactured products. By developing and documenting a comprehensive set of UMP models, more complete knowledge of manufacturing processes can be gained by industry practitioners, leading to continuous improvement of sustainability performance.

C.2. Introduction

Energy consumption in the United States is projected to grow in the industrial sector from 30.46 quadrillion BTUs (32.1 EJ) in 2011 to 38.33 quadrillion BTUs (40.4 EJ) in 2040 [5], or 26% growth in 29 years (annual growth of 0.9%). Energy consumption can be linked to water consumption [267], which is of growing concern [268]. In the United States, water consumption is projected to grow from 114 billion gallons per day (bgd)

(432 GL) in 2005 to 136 bgd (514 GL) in 2030 [7], a 19% growth over 25 years (annual growth of 0.8%). Gutowski et al. [6] reported global per capita manufacturing energy consumption was 467 watts/person in 2010 and was growing at a rate of 1.6% annually. They also reported global per capita emissions of carbon dioxide from industrial activities was at 0.9 tons/person/year and was growing at a rate of 2.5% annually – a significantly higher annual rate than energy or water.

Lozano [101] advanced the representation of sustainability from the common Venn diagram of environmental, social, and economic aspects to a representation wherein all three aspects are overlaid and time is integrated by connecting the present with the future, creating a doughnut shape. This representation forces decision makers to account for the future within the present. Jovane et al. [1] argued that competitive sustainable manufacturing (CSM) is how businesses can continue to grow the global economy while ensuring that a “desirable and acceptable future” is created. Furthermore, they stated that public administrations (PAs) create initiatives that promote the growth and acceptance of sustainable development. In the search for a definition for sustainable manufacturing, Haapala et al. [46] expanded the Department of Commerce’s (DOC) definition to include the closing resource loops within product manufacturing. Zhang et al. [77] defined sustainable manufacturing as “ the set of systems and activities for the creation and provision of manufactured products that balance benefits for ecological systems, social systems and economic systems.”

Haapala et al. [46] identified two main directions that technology can be advanced: by developing products themselves and by developing manufacturing processes and manufacturing systems. Along with advancing technology, measurement is necessary to validate that advancements exhibit improved sustainability performance over their predecessors. A variety of approaches have been reported in literature to undertake such assessments. Ness et al. [97] categorized sustainable assessment methods into three categories: 1) indicators and indices (e.g. the human development index), 2) product-related assessments (e.g. life cycle assessment (LCA)), and 3) integrated assessments (e.g. a combination, e.g., incorporating risk into LCA).

The assessment method applied herein is an expansion on life cycle assessment. This method enables highly detailed manufacturing analysis by developing mathematical models of unit manufacturing processes that instantiate sustainability criteria from mechanics, physics, and operating characteristics. This area of research has been termed unit manufacturing process characterization [20]. Unit manufacturing process (UMP) modeling can provide manufacturing analysis for energy reduction and sustainability improvement areas by analyzing manufacturing at the smallest unit level. UMPs were defined by the National Research Council [15] as "the individual steps required to produce finished goods by transforming raw material and adding value to the workpiece as it becomes a finished product."

Many UMP models have been reported in literature, e.g., Mani et al. [20], Kellens [73], and Dixit et al. [54]. Most modeling efforts have focused on processes known to be highly energy or material intensive; this leaves important gaps in a complete analysis of manufacturing systems. One area that remains unreported is non-destructive surface defect inspection processes. The goal of the research herein is to provide an analysis and modeling of two inspection UMPs: magnetic particle inspection and penetrant inspection. A methodology used for the research is next presented in Section 2. An overview of the two inspection processes is then presented in Section 3. The UMP models are developed in Section 4 and, finally, a summary and conclusions are presented in Section 5.

C.3. Unit Manufactuing Process Modeling

Unit manufacturing process modeling can be traced back to the call for research by the U.S. National Research Council (NRC) in 1995 [15]. Initial UMP models developed in the early 2000s investigated specific processes using ad hoc methods, e.g., [31], [269],

[270], [30], [271]. More recent methods have attempted to standardize the specific modeling aspects, i.e., boundary criteria and evaluation criteria, and include UPLCI [50], [99] and CO2PE! [34], [35]. Researchers at the U.S. National Institute of Standards and Technology (NIST) have developed information models usable for UMPs [20], [191]. The methods reported previously by the UPLCI and CO2PE! Initiatives have focused on environmental evaluation criteria. The work herein expands on those criteria to include economic and social aspects as well.

This work is a continuation of prior research in UMP modeling by the authors. Prior work includes investigative research into analysis and decision support methods by Eastlick et al. [80], [272], further development and application of the modeling methods by Eastwood et al. [33], [273], and development of a software tool by Garretson et al. [112].

C.3.1. Unit Manufacturing Process Modeling Method

The overall methodology is shown in Figure C.1, but steps with a dashed border are not followed. Excluded steps are used for assessments, whereas the methodology implemented here is for UMP characterization. UMPs are first characterized, then bottom-up assessments are completed using characterized UMPs [20].

In the first step, develop project plan, UMP characterization is selected as a sub-methodology. In UMP characterization, also called UMP modeling, a specific UMP is identified, which includes identifying sub-processes, boundaries, and functional unit. The relevant evaluation criteria to be modeled are then identified. The UMP is analyzed as a constituent of its elements (sub-processes), which requires the development sub-process plan. Literature and in-field data are collected for modeling. Finally, the characterized UMPs are reported. Mani et al. [20] utilize information models for representing manufacturing information, and Kellens et al. [34] describe a report format used in the CO2PE! database [206]. The UMP models are reported via this article.

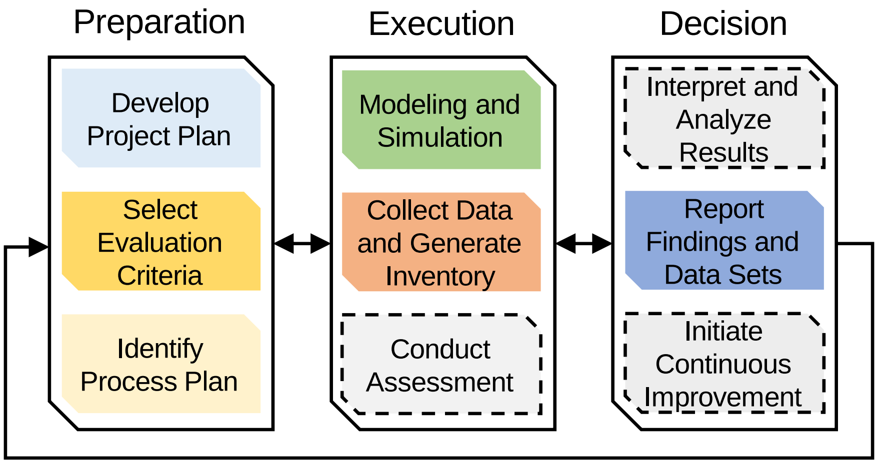

Figure C.1: Sustainable Manufacturing Characterization Methodology (dashed steps not included in UMP modeling).

A schematic input-output model for a unit manufacturing process n can be seen in Figure C.2. This model shows the process transforming material into a product, which would be the input “blank” for process n+1. Using this representation, general inputs and outputs are identified, models relating inputs to outputs are developed, and inputs and outputs are related to the evaluation criteria. The system boundary is represented as a box, and is later expanded in Figure C.8.

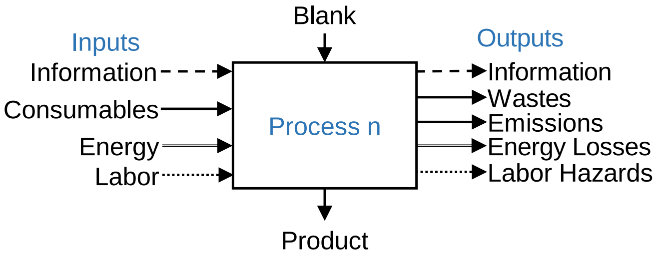

Figure C.2: Schematic unit manufacturing process model

The functional unit (measure of a process or system used for comparison of impact) for a UMP is usually derived from the function of the UMP and often represented as the amount of material processed per production time, e.g., for a milling process the functional unit could be one cubic centimeter of material removed per second [34].

Before describing the UMP developed herein for defect inspection, an overview is next presented to introduce non-destructive inspection methods.

C.4. Overview of Inspection Methods

The first nondestructive inspection method for metals was visual inspection, with and without magnification, which proved to be limited in detection ability and was time consuming [274]. Improved and more reliable methods have since been developed, Bray and McBride [274] have categorized these methods as shown below.

1. Visual and optical methods
2. Nuclear radiation methods
3. Acoustic and dynamic methods
4. Magnetic and electrical field methods
5. Penetrant and chemical methods

Other methods (e.g., thermal methods, microwave materials analysis, and leak testing)

The two inspection methods modeled in this paper are magnetic particle inspection and penetrant inspection. Magnetic particle testing can be traced back to the 1920s, while penetrant testing was used in the 1930s [274]. Magnetic particle inspection is modeled here because it is the most widely adopted method for ferromagnetic alloy inspection. Penetrant inspection is also modeled because it is a widely used process for non-ferromagnetic alloys. Both are non-destructive testing methods used to identify cracks, porosity, and surface discontinuities. These methods involve applying a visually apparent non-interactive material (a liquid) to the surface of a part to highlight the irregularities on the part’s surface. After applying these liquids, the component under inspection is then viewed under an ultraviolet light source, thus highlighting cracks and porosity (Figure C.3). Non-defect characteristics are also apparent using inspection methods, for example, the figure shows a cold working pattern.

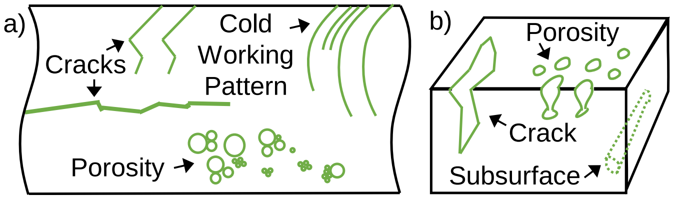

Figure C.3: Cracks, porosity, subsurface defects, and non-defects are highlighted by inspection, Example a) top view and b) side view. (Adapted from Betz [275] and Betz [276]).

Different materials will undergo different production and forming techniques, and each of these can result in common and unique failures and various surface discontinuities. Common classification of surface discontinuities include type, dimension and shape, origin, material of occurrence, or process of cause [275]. The two defect types shown are the common defects identified by the manufacture. This section continues below with specific background information for both magnetic particle inspection and penetrant inspection.

C.4.1. Magnetic Particle Inspection

Magnetic particle inspection utilizes the ferromagnetic properties of the workpiece material and the particulate to indicate irregularities. When magnetized, the workpiece creates a standard magnetic field, in which discontinuities will cause distortion in the magnetic field and attract ferromagnetic particles [276]. Each of these magnetic distortions is called a leakage field (Figure C.4), many are generated by part surfaces. Note that minimal occurrence of distortion results from scratches [276].

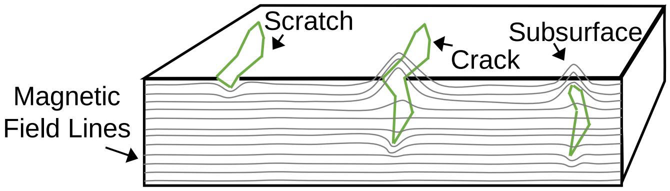

Figure C.4: Leakage fields extending beyond surface of component (Adapted from Betz [276]).

Defects do not have to be open to the surface, but instead can be relatively close to the surface and still distort the magnetic field; paint or debris-filled cavities can also be detected [276]. Figure C.3 provides defect examples, precise examples can be found in Betz [276] and Bray and McBride[274]. Magnetic flux orientation must occur transverse to the defects, and causes an operator to remagnetize the component several times in different orientations [274].

Often, particulate size and shape must meet required specification to adhere properly to a component with a magnetic flux. Particles will wear over time and must be replaced. Colored particles are often used, and, for the process studied herein, the particulate was fluorescent and visible under ultraviolet (UV) light. The analysis of the process is for a standalone unit, with a bath and a magnetizing coil having a certain diameter.

It is sometimes the case when the component is larger than the coil-loop used for magnetization and direct contact magnetization would be where other methods cannot be utilized [277]. In this case, positive and negative leads are connected to the part and a magnetic field is induced through current flow. Larger components may require several magnetizing steps to ensure adequate magnetic field density.

Demagnetization is often completed following inspection, although not always necessary. Perfect demagnetization is achieved through heating a material to its Curie temperature, which is when the intrinsic magnetic moments change direction, causing permanent magnetism to change to induced magnetism [274]. Unfortunately, this temperature is very near to the austenitic phase change temperature for steels [276], and it is impractical to implement the practice. Other methods will leave residual magnetic fields, no matter how small. The common method is to induce a decreasing magnetic field by following a hysteresis loop, wherein the current is reversed and reduced subsequently several times causing the magnetizing force, H, to reverse, thus causing the induced field, B, to reverse

[276]. Figure C.5 shows the initial magnetization following the dashed line in a), and a demagnetization curve shown in b).

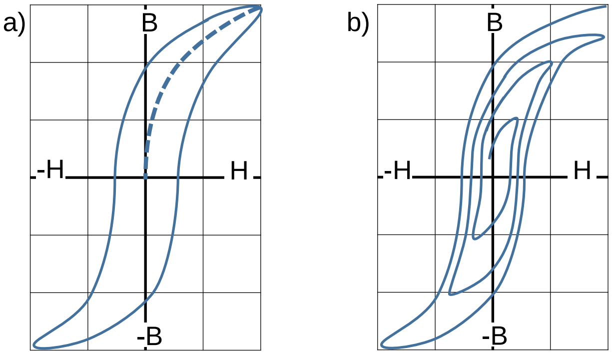

Figure C.5: Hysteresis loop (Induced field, B, and magnitizing force, H). a) initial magnitization, and b) demagnetization (Adapted from Betz [276]).

C.4.2. Penetrant Inspection

Penetrant inspection utilizes capillary forces of a penetrating liquid and a highlighting developing agent to indicate irregularities (Figure C.6). Penetrants are selected based on their capillary action capabilities, and developers are selected by their compatibility with the penetrant and their appearance. Because the developer will highlight all surfaces coated with penetrant, a cleaning step is required in-between application of each. This step is most often a water rinse, to remove only surface penetrant. Oil based penetrants will require an emulsifier to enable the excess to be rinsed with water, this can be an oil-water surfactant.

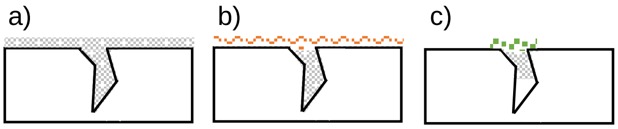

Figure C.6: Stages of penetrant processing. a) penetrant application, b) emulsification, c) developer application (Adapted from Betz [275]).

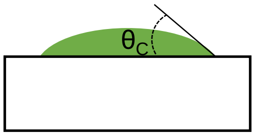

Figure C.7: Contact angle of a liquid on a surface

Unlike magnetic particle inspection, liquid penetrant inspection cannot detect subsurface defects. Subsurface defects cannot be penetrated because they are not exposed. Components are either submerged or sprayed with the penetrant liquid. The penetrant used by the process studied utilized an oil based liquid, but not all penetrant is oil based.

Bray and McBride [274] described several properties of a good-performing penetrant, which include high wetting ability, high surface tension, relatively low viscosity. Wetting is the angle a droplet of liquid makes when contacting a flat solid surface; liquids with contact angles below 90° are said to wet the surface and lower contact angles demonstrate improved wetting ability (Figure C.7). The contact angle will greatly affect how well a liquid can penetrate surface discontinuities. Surface tension of a liquid is caused by cohesive forces between molecules, and also affects the angle a liquid makes when contacting a surface. Viscosity affects the speed at which a liquid will penetrate a void. Lower viscosity is desirable, but very low viscosity liquids may run off the surface of a component before flowing into the voids. Viscosity also affects dragout, the amount of fluid adhering to a part pulled from a bath.

Finally, developing agents can be either a liquid or a powder; a powder was used at the observed process. While many different colors of developer can be used, the observed process used a fluorescent developer that was visible under a UV light.

C.5. Process Models

The inspection process models are developed in this section. First, the evaluation criteria and general models are presented. The system boundary for each process is shown in

Figure C.8. The magnetic particle inspection UMP model is then presented, followed by the penetrant inspection UMP model. UMP models are developed to quantify the evaluation criteria for each UMP. Table C.1 presents the selected evaluation criteria for this study and the respective units. The evaluation criteria are from across the three sustainability aspects to ensure holistic assessment. Metrics are defined relative to the impact a UMP has, thus metric selection is limited. The economic impact is limited to cost incurred during operations, environmental impact are related to energy and material flows of operations, and social impact was defined by how the UMP impacts the operators.

Table C.1: Evaluation criteria and units

Aspect	**Evaluation Criteria**	**Unit**
Economic	Operating Cost	Dollars
Environmental	Energy Use	Kilowatt hours
	Water Use	Liters
	GHG Emissions	Kilograms carbon dioxide equivalence
	Total Waste	Kilograms
Social	Average Wage	Dollars per hour
	Lost Work Days	Number of days

Table C.2 presents the general models used that are further defined for both processes below. Notably, the operating cost, energy consumption, water use, and total waste exhibit unique modeling aspects; i.e., the derivation of each of these evaluation criteria are unique between the two process models. On the other hand, greenhouse gas (GHG) emissions, average wages, and lost work days are generalized for any process model developed. Nomenclature for Table C.2 is described throughout the Process Model Section.

Table C.2: Evaluation criteria and general models

Aspect	**Evaluation Criteria**	**Model Equation**
Economic	Operating Cost ($)	$C^{op} = M^{con} * C^{con} + E^{T} * C^{E} + t^{L} * AWG$
Environmental	Energy Use (kWh)	$E^{T} = \sum P^{i} * t^{i}$
	Water Use (L)	$V^{H2O} = \sum R^{wat,I} * M^{pro,i}$
	GHG Emissions (kg CO^2 eq.)	$EM^{ghg} = E^{con} *(R^{CO2} + R^{CH4} * GWP^{CH4} + R^{N2O} * GWP^{N2O})$
	Total Waste (kg)	$WST^{T} = \sum(R^{land}+R^{inc}+R^{rec}+R^{haz})^{,i}*M^{pro,i}$
Social	Average Wage ($/hr)	$AWG = (1/t^{P}) \sum W^{i} * t^{L,i}$
	Lost Work Days (No.)	$LWD = \sum ILL^{i} *DL^{i} + \sum INJ^{j}*DL^{j}$

Calculation of GHG emissions is common between the two inspection processes; emissions result from electrical energy generation for each. This evaluation criterion is calculated from the production of energy and is show in Table C.2 and Equation C.1. The equation considers emissions rates (R_i) of each chemical for a given energy production amount and global warming potential conversion factors (GWP_i) for chemicals to mass of carbon dioxide equivalence, where the integral heat absorption for a time period for an atmospheric chemical is normalized to that of carbon dioxide. This is multiplied by the total energy used by the process (E_T) to determine the associated GHG emissions.

$$EM_{ghg} = E_T * (R_{CO2} + R_{CH4} * GWP_{CH4} + R_{N2O} * GWP_{N2O}) \tag{C.1}$$

The social evaluation criteria are not unique to individual processes. The first, average wage (AWG), is the sum of the product of the wage for each person (W_i) and their labor time ($t_{L,i}$), divided by the total process time (t_p). See Equation C.2. Note that while average wage is used to calculate operating cost, it can be used to compute relative societal wage, poverty distribution, or personal spending power, which are factors for considering societal growth (an indicator of social impact).

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

Lost work days is a measure for the safety of a UMP. This measure aggregates the days lost per illness and days lost per injury (Equation C.3). Where ILL_i is the number of unique illnesses i, DL_i is the days lost for illness i, INJ_j is the number of unique injuries j, and DL_j is the days lost for injury j. The illnesses and injuries can be represented instead by probability of each illness ($P_{ILL,i}$) and injury ($P_{INJ,j}$) and would take the form of Equation C.4.

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

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

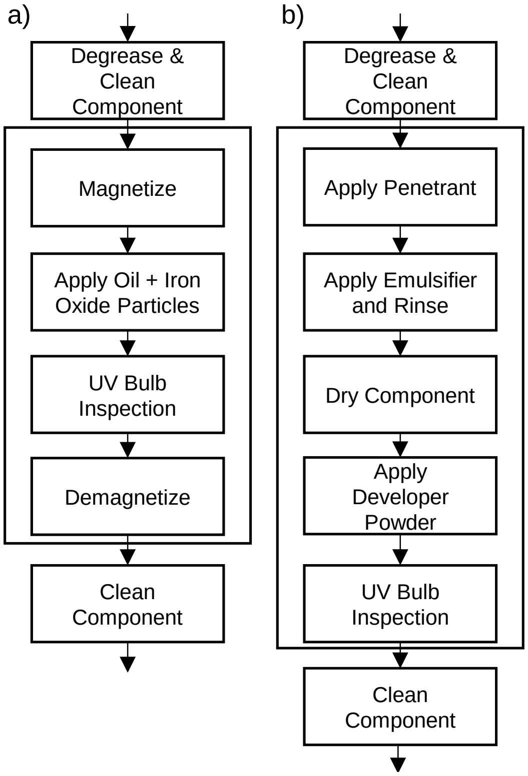

Figure C.8: Manufacturing process flow diagrams for a) magnetic particle inspection and b) penetrant inspection. Outlined sections identify the inspection sub-processes.

Figure C.8 identifies the sub-process flow for both of the inspection UMPs. Immediately prior and following the UMPs are component cleaning and degreasing processes. The prior processes are driven by the requirement for the component to be clean, enabling the metallic particles or penetrant to enter the surface defects. The subsequent cleaning processes would be used to remove any oils or particulates that remain on the component after the inspection. The subsequent process is dependent, however, not on the inspection processes, but whether the following process requires a clean component.

C.5.1. Magnetic Particle Inspection

Of the many types of magnetic particle inspection, a horizontal wet method (Type 2) is modeled [274]. Magnetizing current is supplied from a three phase alternating current (AC) power source. The current is fed through a loop to induce a magnetic field in the part. Iron oxide particles are then held in place at the defect locations by the leakage fields. The component is viewed under a UV light bulb to identify any defects. The component is then demagnetized. This process flow represents the boundary for the magnetic particle inspection UMP, and can be seen in Figure C.8. The model inputs and outputs are normalized to a surface area of ten square centimeters.

The first evaluation criterion, operating cost, is the sum of the per-mass costs (C_i) for each unit of material mass used (M_i), total energy consumed (E_T), and all labor required in the process (Equation C.5). The consumables considered include oil, iron oxide, and the UV light bulbs. Each is scaled by a ratio between the process time (t_p) and the time between replacement (t_{BTR_i}), wherein the latter includes only operating hours. The calculation for energy can be seen in Equation C.6. The last term multiplies the average wage calculated in Equation C.2 by the process time.

$$C_{op} = (M_{OIL} * C_{OIL} + M_{FeO2} * C_{FeO2}) * (t_p/t_{BTR\_OIL}) + M_{UV} * C_{UV} * (t_p/t_{BTR\_UV}) + E_T * C_E + AWG * t_p \tag{C.5}$$

The energy calculation for the process is a sum of the magnetizing energy and the UV bulb energy. This can be seen in Equation C.6, where E_T is the total energy, E_{mag} is the magnetizing energy, E_{dem} is the demagnetizing energy, and E_{UV} is the UV bulb energy. First, the magnetizing energy is derived below, followed by the bulb energy.

$$E_T = E_{mag} + E_{dem} + E_{UV} \tag{C.6}$$

The energy to magnetize (and demagnetize) the component is derived from the relationship of power (P_{mag}), time (t_{mag}), and energy (E_{mag}) shown in Equation C.7, and

Ohm's law, wherein power is equivalent to current (I_{wire}) squared times the resistance (R_{Ω}) of the wire (Equation C.8).

$$E_{mag} = P_{mag} * t_{mag} = E_{dem} \tag{C.7}$$

$$E_{mag} = I_{wire}^{2} * R_{\Omega} * t_{mag} \tag{C.8}$$

Before elaborating on finding the resistance and current, the demagnetizing energy is examined. The demagnetizing energy (E_{dem}) can be calculated using the similar equations to those for the magnetizing energy. For simplicity, stages of reversing and decreasing DC current are used instead of stages of AC current, and end results are the same; some 30 stages are used [276]. The demagnetizing current is found by in Equations C.9 and C.10 by summing each stage of smaller current flow. Finally, the currents for each stage are found by subdividing the magnetizing current I_{wire} 30 times, see Equation C.11; stage 30 would be considered the initial demagnetizing stage. Finally, $t_{dem,i}$ represents the time spent at each stage i.

$$E_{dem} = \sum P_{dem,i} * t_{dem,i} \tag{C.9}$$

$$E_{dem} = \sum I_{wire,i}^{2} * R_{\Omega} * t_{dem,i} \tag{C.10}$$

$$I_{wire,i} = I_{wire} * i/30 \tag{C.11}$$

The resistance of the wire is calculated as in Equation C.12. Where ρ_{Ω} is the electrical resistivity of the wire and is the inverse of the electrical permissivity ($1/\sigma_{\Omega}$). L_{wire} and A_{wire} are the length and cross sectional area of the wire. L_{wire} can be found using the circumference of a circle multiplied by the number of wraps the wire makes around the loop. R_{Loop} is the radius of the loop and N_{loop} is the number of wraps in the loop. A_{wire} is found using the radius of the wire R_{wire}. Equation C.13 is developed as a result of substitution.

$$R_{\Omega} = (\rho_{\Omega}) * (L_{wire}/A_{wire}) \tag{C.12}$$

$$R_{\Omega} = (1/\sigma_{\Omega})*(2*\pi*R_{Loop}* N_{loop})/(\pi*R_{wire}^{2}) \tag{C.13}$$

The second necessary term, the required current to magnetize the component is needed and can be derived using two methods: first, using the equations from elementary physics, and second, using empirical equations from an ASTM standard [277]. Using elementary physics, it is assumed that the required magnetic B-field (B) is known. The current can then be calculated from the Biot-Savart law, Equation C.14, assuming the current is constant.

$$I_{wire} = 4\pi B/(\mu_0 \int_{wire}(dl \text{ X } \hat{r}/|r|^2)) \tag{C.14}$$

B is the magnetic flux density, μ_0 is the magnetic constant ($4\pi*10^{-7}$T-m/A), $\int_{wire} dl$ is the line integral of the length of the wire, r is the distance vector between the component and the wire, and $\hat{r}$ is the unit vector of r and is crossed with dl. ASTM identifies the minimum magnetic B-field strength to be 0.003 T (30 G) [277], which can be measured with a Tesla meter (also known as a Gauss meter). A complete derivation for the magnetic fields was performed by Edwards and Palmer [278], and is outside the scope of this paper.

The alternative and mathematically simpler method for determining the required current, and thus the energy, is to use the empirically derived equations developed by the ASTM standard for magnetic particle testing [277]. These equations use the constants K_1, K_2, or K_3 (amps) to relate the required current to the size of the component, and the geometries of the magnetizing loops. The equations are selected based on the fill factor Y, which is a ratio between the cross sectional area of the magnetizing loop and the component, see Equation C.15. Equation C.16 is used to account for hollow parts, where D_{eff} is the effective diameter. Where D_{out} is the outer diameter of the part and D_{in} is the inner diameter of the part.

$$Y = \pi * R_{Loop}^2/(\pi * D_{out}^2/4) \tag{C.15}$$

$$D_{eff} = [D_{out}^2 - D_{in}^2]^{1/2} \tag{C.16}$$

For small parts with low fill factor, values of Y greater than 10, Equations C.17 and C.18 are used, where Equation C.17 is used for those placed next to the loop and Equation C.18 for components placed in the center of the loop. Equation C.19 is used for Y values between 2 and 10, and is a ratio high fill factor and low fill factor current values, where I_{lf} is the current calculated using Equation B.17 and I_{hf} is that from Equation C.20. Finally, Equation C.20 is used for low Y values, i.e., large parts.

$$I_{wire} = K_1/(L_{cmp}/D_{eff})*(1/N_{loop}) \tag{C.17}$$

$$I_{wire} = K_2*R_{Loop}*[1/((6\ L_{cmp}/D_{eff})-5)]*(1/N_{loop}) \tag{C.18}$$

$$I_{wire} = I_{hf}*(10-Y) + I_{lf}*(Y-2)/8 \tag{C.19}$$

$$I_{wire} = K_3*[1/((L_{cmp}/D_{eff}) + 2)]*(1/N_{loop}) \tag{C.20}$$

Calculating the power from a light bulb is straightforward: identify the wattage of the bulb and multiply that by the time it is on. This is seen in Equation C.21.

$$E_{UV} = P_{UV} * t_{light} \tag{C.21}$$

Where E_{UV} is the energy consumption of the bulb, P_{UV} is the power of the bulb, and t_l is the time the light bulb is on. UV bulbs used for defect inspection require a minimum irradiance. If only the irradiance is known, then the wattage can be calculated from Equation C.22 [279].

$$P_{UV} = 2\pi(1-\cos(\alpha/2))*IR*(L_2/L_1)^2 \tag{C.22}$$

Where α is the solid angle, IR is the irradiance at the measurement distance, L_2 is the measurement distance, and L_1 is a standard distance of one meter.

The total waste generated from the process can be calculated as a sum of the landfill waste, the recycled waste, and the hazardous waste as seen in Equation C.23. It is assumed here that after some time the iron oxide particle geometry will decay and thus no longer be usable. After this time, the oil-particulate mixture will have to be replaced. The oil is assumed to be recycled and the remaining particulate-oil sludge is considered a hazardous waste and further treated. It is also assumed that the UV light bulbs must be replaced periodically, with the spent bulbs sent to a landfill. The masses are scaled by the ratio of process time to time between replacement similar to Equation C.5.

$$WST_T = (M_{OIL}+M_{FeO2})*(t_p/t_{BTR\_OIL}) + M_{UV}*(t_p/t_{BTR\_UV}) \tag{C.23}$$

C.5.2. Penetrant Inspection

The penetrant inspection process model was developed through observation of a penetrant inspection process that involved several work stations within a manufacturing work cell. These included a penetrant tank, a rinsing tank, a developer powder application area, a drying oven, and a dark room. The steps for the penetrant inspection process can be seen in Figure C.8. Bray and McBride [274] classified different groups of penetrants, and the observed process belongs to their group 5.

The first evaluation criteria, operating cost, is calculated using Equation C.24, where the costs can be calculated as a function of penetrant consumption, emulsifier consumption, water consumption, powder consumption, UV bulb consumption, energy consumption, and labor. The penetrant is not replaced, so consumption is caused by dragout and carry-off, consumption of emulsifier and developer powder are also calculations of carry-off (Equations C.25-C.27). Water is used in rinsing after the penetrant tank (Equation C.35). The UV bulb and wage calculations are the same as that for magnetic particle testing. The energy calculation is in Equation C.28.

$$C_{op} = M_{PEN} * C_{PEN} + M_{EMU} * C_{EMU} + M_{H2O} * (C_{H2O} + C_{WW}) + M_{PWD} * C_{PWD} + M_{UV} * C_{UV} * (t_p / t_{BTR\_UV}) + E_T * C_E + AWG * t_p \tag{C.24}$$

The mass of penetrant used (M_{PEN}), mass of emulsifier (M_{EMU}) the mass of developer powder used (M_{PWD}) are calculated using Equations C.25-C.27, respectively. Wherein A_{part} is the surface area of the component, ρ_{PEN} is the density of the penetrant, L_{PEN} is the thickness of the penetrant coating, ρ_{PWD} is the density of the powder, and L_{PWD} is the thickness of the powder coating.

$$M_{PEN} = A_{part} * \rho_{PEN} * L_{PEN} \tag{C.25}$$

$$M_{EMU} = A_{part} * \rho_{EMU} * L_{EMU} \tag{C.26}$$

$$M_{PWD} = A_{part} * \rho_{PWD} * L_{PWD} \tag{C.27}$$

The energy calculation for the process is a sum of the oven energy, the bulb energy, and any peripheral equipment (Equation C.28). The penetrant inspection process observed did not use conveyers, or spray nozzles, thus peripheral energy (E_{ph}) is not be derived. In Equation C.28, E_T is the total energy, E_{oven} is the oven energy and E_{UV} is the UV bulb energy. The oven energy is derived (Equations C.29-C.34), and Equations C.21 and C.22 can again be used to calculate the energy for using the UV bulb.

$$E_T = E_{oven} + E_{UV} + E_{ph} \tag{C.28}$$

The oven used in the observed UMP used electric heating elements as the heat source. Because it was used to dry the component, it operated at a low, constant temperature. The oven was a closed volume and had insulated walls and interior shelving. Components were dried for approximately 10 minutes, and were typically processed in a batch. The energy for the oven (E_{oven}) is calculated using Equation C.29, where E_{heat} is the theoretical required heat (energy) and μ_{oven} is the efficiency of the oven. The theoretical required heat is calculated in Equation B.30 as a thermodynamic theoretical minimum of the sum of the heat of the air (q_{air}), the carried off heat of the part (q_{part}), and the heat lost through walls of the oven (q_{loss}).

$$E_{oven} = E_{heat} * \mu_{oven} \tag{C.29}$$

$$E_{heat} = (q_{air} + q_{part} + q_{loss}) * t_{oven} \tag{C.30}$$

The heats for the air, part, and wall losses are calculated in Equations C.31-C.33, respectively, where cp_i is the heat capacity of i, m_i is the mass of i, T_{oven} is the temperature of the oven and T_{room} is the ambient temperature, k is the heat transfer coefficient, A_{wall} is the oven wall surface area, and L_{wall} is the thickness of the oven wall.

$$q_{air} = cp_{air} * m_{air} * (T_{oven} - T_{room}) \tag{C.31}$$

$$q_{part} = cp_{part} * m_{part} * (T_{oven} - T_{room}) \tag{C.32}$$

$$q_{loss} = k * A_{wall} * (T_{oven} - T_{room}) / L_{wall} \tag{C.33}$$

Alternately, Equation C.34 can be used to calculate the energy consumption of an electric oven [280]. This is an empirical equation and incorporates forced air flow (R_{air}). Here, E_{oven} is in kilowatt hours, R_{air} is in standard cubic feet per minute (SCFM), T_{oven} and T_{room} are in Fahrenheit, and t_{oven} is in hours.

$$E_{oven} = (q_o * (T_{oven} - T_{room}) * 1.2/3000) * t_{oven} \tag{C.34}$$

The total water used for the process is calculated based on the water used in the penetrant application step and the developer powder step. The water used for cleaning before and after the penetrant inspection process would be allocated to cleaning processes (Figure C.8), and is not accounted herein. Equation C.35 calculates the total water (V_{H2O}) using the flow rate of water (R_{H2O}) and the time the water is flowing (t_{H2O}).

$$V_{H2O} = R_{H2O} * t_{H2O} \tag{C.35}$$

The total waste generated is a function of the landfill waste and effluents carried off by the water rinse and subsequent cleaning process (Equation C.36).

$$WST_T = M_{PEN} + M_{EMU} + M_{PWD} + M_{UV}*(t_p/t_{BTR\_UV}) \tag{C.36}$$

At the observed facility, all waste water was processed on site to remove the effluents. Filtering separated particulates, emulsifiers, and oil from the water. The particulates are treated as hazardous waste, and the oil and emulsifier is recycled.

A similar inspection process was observed for large components (those not able to fit in the penetrant tank or the drying oven, or which were too heavy to lift). A notable difference for the large component penetrant process was that the process was completed using one large machine. Differences relevant to modeling included a conveyor for component movement, spray nozzles for penetrant application, and the oven volume and larger wall area.

While the effects of scrap rates and inspection errors are not considered in this study, increases in scrap and errors will negatively impact sustainability performance of product manufacturing (through increased production time and resource) and use (through increased failure rates). A Type 1 error (a false positive) would falsely allocate impact of scrap to the UMP for an acceptable part. Likewise, a Type 2 error (false negative) would artificially reduce the scrap rate, resulting in falsely high sustainability performance for the product.

C.6. Discussion

Unit manufacturing process (UMP) modeling was developed to increase the detail of sustainability assessments of manufacturing processes and systems. Magnetic particle inspection and penetrant inspection were modeled here to characterize the surface defect inspection process for both ferromagnetic and non-ferromagnetic alloys. These UMPs were modeled using seven evaluation criteria to capture the three aspects of sustainability. Furthermore, as more UMP models are developed and published, enabling the congruity (composability) between each UMP model is imperative.

The flow aspects of the two models developed highlight interesting questions regarding the composability of UMP models. The first question is, what are differences between the requirements of the two processes that impact model input parameters? Design requirements dictate the selection of one of these two processes, but unique characteristics (requirements and consequences) of the processes drive the characteristics of the manufacturing process flows. For example, both inspection processes require that the component is clean of debris and oils. This requirement dictates a degreasing and rinsing processes occur prior to inspection.

Further, it is postulated that characteristics of the component state (e.g., material type and condition) can dictate the order in which manufacturing processes occur. Thus, tracking the state of the component can increase the accuracy of UMP modeling for sustainable manufacturing characterization and assessment. This can give rise to information transfer between UMP models and enable composability of UMP models. A component state model would not necessarily require mathematical formulation, but would need to track specific information relevant to the UMP models (e.g., part geometry and material microstructure). This component state model could serve as an information transport mechanism between UMP models representing a process flow.

Finally, future work specific to this study includes evaluating entire manufacturing process flows that include these inspection processes to better identify composability characteristics of these UMPs. Future work also includes necessary mathematical model validation, and the implementation of the models in a realistic application.

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C.8. Disclaimer

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