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Title: Process Information Modeling for Characterizing Sustainability Performance of Cyclic Manufacturing Processes

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Sustainability has become an unprecedented priority in global manufacturing due to the growing concerns over issues such as an aging workforce, environmental degradation, and public health. The simultaneous consideration of the economic, environmental, and social aspects – often referred to as the "three pillars of sustainability" – is crucial to the pursuit of sustainable manufacturing. To achieve the goal of environmentally responsible manufacturing, a key aspect of sustainable manufacturing, industrialists and researchers in the manufacturing community must characterize process energy impacts to improve both the economic and the environmental performance of manufacturing operations. Flexible and rapid manufacturing processes are gaining traction due to their suitability for the production of parts exhibiting complex geometries and the use of advanced materials. The technical limitations and environmental concerns of conventional unit processes and sequential process flows have led to widespread adoption of advanced manufacturing processes that exhibit cyclic nature, termed cyclic manufacturing processes. Manufacturing technology research has focused on developing additive and hybrid processes, which exhibit a cyclic nature and enable flexible and rapid production, effectively shortening the time-to-market, decreasing the manufacturing process chain, and reducing production costs. With the growing adoption of cyclic manufacturing

processes as an alternative to conventional unit processes and sequential process flows, it is necessary for developers and users of these technologies to incorporate broader sustainability considerations during process development, product design, and process planning activities. However, characterization of cyclic manufacturing processes, such as hybrid manufacturing processes, is a challenge due to the complex, integrated, cyclic nature of subprocesses, which require a higher level of information synthesis than individual, or unit, manufacturing processes. The overarching goal of this research is to facilitate environmental performance modeling of cyclic manufacturing processes by developing a uniform process information modeling methodology comprising of a manufacturing process modeling framework and an information modeling framework. Such a methodology will enable characterization, assessment, and extraction of product and process sustainability information through model reusability, extensibility, and composability. Achieving this goal will enable the modeling of hybrid manufacturing process and advance the sustainability evaluation of cyclic manufacturing processes.

Process Information Modeling for Characterizing Sustainability Performance of Cyclic Manufacturing Processes

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.

Sriram Manoharan, Author

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CONTRIBUTION OF AUTHORS

Chapter 3: Manuscript 1

Sriram Manoharan led the development of the manufacturing process modeling framework for characterizing sustainability performance of cyclic manufacturing processes, development of terminology and mathematical representation of product and process sustainability information, development of a unit manufacturing process (UMP) aggregation and quantification algorithm to evaluate sustainability performance of cyclic processes, application of the developed methodology to characterize a low-cost, hybrid additive-subtractive process, comparing the performance of a conventional subtractive processes based on the resulting system model, and authoring of the manuscript. Prof. Karl Haapala provided guidance throughout the work, including model development, analysis, and manuscript review and feedback.

Chapter 4: Manuscript 2

Sriram Manoharan led the development of the information modeling framework for assessing cyclic manufacturing processes, providing information modeling guidelines based on the developed framework, development of a prototype information model for a hybrid manufacturing system composed of fused filament fabrication (FFF), an additive process, and computer numerically-controlled (CNC) milling, a subtractive process. Prof. Karl Haapala provided guidance throughout the work, including framework development, modeling guidelines, and manuscript review and feedback.

Chapter 5: Manuscript 3

Sriram Manoharan led the development of the polymer-based hybrid additive-subtractive manufacturing process, development of a mechanistic model for evaluating process energy consumption, development of experimental procedures, development of comparison baselines for evaluating model effectiveness, analysis of results, and authoring of the manuscript. An undergraduate research assistant, Dustin Harper, assisted with conducting experiments, including creation of CAD models for the parts to be fabricated, energy monitoring, and data collection. Prof. Karl Haapala provided guidance throughout the work, including process development, experimental procedures, data analysis, and manuscript review and feedback.

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CHAPTER 1. INTRODUCTION

1.1 Motivation

Sustainability has become an unprecedented priority in global manufacturing due to the growing concerns over issues such as an aging workforce, environmental degradation, and public health [1].The integration of manufacturing and sustainability creates an effective infrastructure for academia and industry to strive towards meeting the needs of a developing global society [2]. Sustainable manufacturing has been defined by the U.S. Department of Commerce as *[t]he creation of manufacturing products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers, and are economically sound* [3]. This simultaneous consideration of the economic, environmental, and social aspects – often referred to as the "three pillars of sustainability" – is crucial to the pursuit of sustainable manufacturing.

To achieve the goal of environmentally responsible manufacturing, industrialists and researchers in the manufacturing community must characterize their energy impacts to improve both the economic and environmental performance of their operations [4]. In fact, according to the Annual Energy Outlook 2018 [5] published by the U.S. Energy Information Administration, the industrial sector accounts for 32% of all energy consumed in the United States (Fig. 1.1); while manufacturing alone accounts for 66% of the industrial sector's energy consumption.

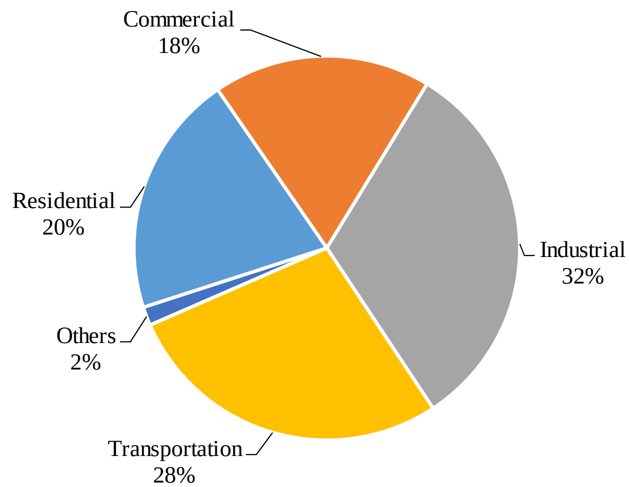

Figure 1.1: Energy consumed by the economic sectors in the United States [5]

While extraction of energy resources can have a detrimental impact on the environment, conversion of these feedstocks into energy results in the generation of greenhouse gases, which have been linked to climate change [6]. Globally, industrial energy use accounts for about one-third of greenhouse gas emissions [7]. Continual reduction of process energy consumption through increased efficiency is being pursued to strengthen the economic vitality of U.S. manufacturers, while also helping to protect our environment [1].

While manufacturers have undertaken efforts to improve the environmental performance of individual manufacturing processes (UMPs), flexible and rapid manufacturing processes are gaining traction due to their suitability for the production of parts exhibiting complex geometries and the use of advanced materials [1]. The technical limitations and environmental concerns of conventional unit processes and sequential process flows have led to widespread adoption of advanced manufacturing processes that exhibit a cyclic nature. Manufacturing technology research has focused on developing additive and hybrid processes, which exhibit a cyclic nature and enable flexible and rapid production, effectively shortening the time-to-market, decreasing the manufacturing process chain, and reducing production costs [8]. These processes have been termed cyclic manufacturing processes, and defined as “a manufacturing process in which the parts are produced repeating a sequence of subprocesses that forms the manufacturing cycle” [9]. With the growing development and adoption of advanced cyclic manufacturing processes, it is critical to understand the mechanistic behavior, of each subprocess to accurately quantify and continuously improve process performance metrics [9]. A mechanistic behavior is one which describes the physics of a complex system by examining the workings and establishing the relationship of its individual parts [10].

1.2 Background

Cyclic manufacturing processes enable flexible and rapid production of parts by repeating a physical sequence of subprocesses for each part feature, forming a manufacturing cycle with consistent or varying process parameter settings. Advanced manufacturing processes such as additive and hybrid manufacturing processes represent cyclic manufacturing processes. For example, subprocesses that describe the cyclic nature of a laser powder bed fusion additive process include spreading a layer of powder, melting the powder, and lowering the build platform for the next layer [11].

In recent years, advanced cyclic processes, termed hybrid manufacturing processes, are increasingly being recognized as a means to meet production goals, such as reducing equipment and space needs, and shortening processing, inspection, and handling times [12]. According to Zhu et al. [13], hybrid manufacturing processes open up new opportunities and applications for manufacturing various components, which cannot be produced efficiently using standalone processes. In the context of the research presented herein, a hybrid process is a synergistic combination of an additive and a subtractive process exhibiting a cyclic nature in a single machine for improving part quality, part functionality, and manufacturing productivity [14]. While prior work has been conducted to understand the performance of integrated processes and process planning for hybrid processes, no studies have been reported that investigate the energy, materials, or cost impacts of using hybrid processes in production environments.

ASTM International has recently published standards, such as ASTM E2986-15 [5] and ASTM E3012-16 [6], to provide a uniform methodology for representing manufacturing processes, enabling the consistent evaluation of changes in environmental impacts due to modifications in individual manufacturing processes. While the sustainable manufacturing community has applied these standards in modeling individual manufacturing processes, there exists limited research in characterizing environmental impacts of cyclic manufacturing process which have a complex, integrated, and cyclic nature of subprocesses.

1.3 Problem Statement

With the growing adoption of cyclic manufacturing processes as an alternative to conventional unit processes and sequential process flows, it is necessary for developers and users of these technologies to incorporate broader sustainability considerations during process development, product design, and process planning activities. However, characterization of cyclic manufacturing processes, such as a hybrid process, is a challenge due to the complex, integrated, and cyclic nature of subprocesses, which require a higher level of information synthesis than individual processes.

1.4 Research Objectives

The overarching goal of this research is to facilitate environmental performance modeling of cyclic manufacturing processes by developing a uniform process information modeling methodology comprising of a manufacturing process modeling framework and an information modeling framework. These frameworks will enable characterization, assessment, and extraction of product and process information through model reusability, extensibility, and composability. Achieving this goal will enable the modeling of hybrid manufacturing process and advance the sustainability evaluation of cyclic manufacturing processes.

1.5 Research Questions

From the research objectives stated in the previous section, the following research questions are derived:

Question 1: What modifications to the current ASTM standards, in terms of structure and formalization, are required to represent cyclic manufacturing processes for manufacturers to evaluate, document, and improve process sustainability performance?

Question 2: How must information of cyclic manufacturing processes be represented so that it can be easily implemented into a software application for sustainability characterization and assessment?

Question 3: How can the effectiveness of a standards-based model be evaluated for characterizing environmental impacts of cyclic manufacturing processes?

1.6 Research Tasks

To help pursue the research objective and to answer the derived research questions, the following research tasks were undertaken:

Task 1: Develop a manufacturing process modeling framework based on the ASTM 3012-16 standard [16] to facilitate sustainability performance characterization of cyclic manufacturing processes. The framework should enable characterization, assessment, and extraction of product and process information through model reusability, extensibility, and composability.

Task 2: Develop an information modeling framework for sustainability assessment of cyclic manufacturing processes. Based on the developed framework, provide information modeling guidelines for UMP model developers and UMP performance analysts to construct and analyze cyclic processes. The resulting guidelines should support development of a prototype information model for a hybrid manufacturing process composed of FFF (an additive process) and CNC milling (a subtractive process).

Task 3: Utilize the developed standards-based cyclic framework to characterize environmental performance of a hybrid manufacturing process. Evaluate the effectiveness of the resulting model for characterizing energy consumption in a hybrid manufacturing process.

1.7 Thesis Outline

The research herein is presented in the manuscript format consisting of six chapters. Chapter 1 provides summarizes the motivation, background, objective, and tasks of the research. Chapter 2 provides a review of prior work reported in the literature for characterization of manufacturing process energy use, unit manufacturing process modeling approaches, information modeling methods, and cyclic manufacturing processes.

Chapter 3 is an article submitted to the *International Journal of Sustainable Manufacturing* and describes the manufacturing process modeling framework for characterizing sustainability performance of cyclic manufacturing processes. Applications of this research will enable users of cyclic processes to develop energy saving strategies during product design and process planning.

Chapter 4 is a conference article published in *Procedia CIRP (Proceedings of the CIRP 2019 Life Cycle Engineering Conference (CIRP LCE 2019))*, and provides an information modeling framework that will enable sustainability performance assessment of cyclic manufacturing processes through the composition of UMP models. The developed software framework and information modeling guidelines will enable UMP model developers and analysts to create and compose information models for performing sustainability characterization of cyclic manufacturing processes.

Chapter 5 is an article to be submitted to the *Journal of Manufacturing Systems* and reports the developed cyclic model for characterizing energy consumption of hybrid manufacturing processes. The effectiveness of the developed cyclic model is evaluated utilizing several baselines of comparison for a dual-extrusion hybrid manufacturing process developed at Oregon State University under this research.

Chapter 6 offers a summary, conclusions, research contributions, and opportunities for future work.

CHAPTER 2. LITERATURE REVIEW

As noted in the Chapter 1, this research aims to facilitate sustainability performance characterization of cyclic manufacturing processes by developing a manufacturing process modeling framework and an information modeling framework. This chapter provides a review of prior work reported in the literature for characterization of manufacturing process energy use, unit manufacturing process modeling, and information modeling methods, and cyclic manufacturing processes. This chapter expands upon the prior work reported in the three manuscripts comprising this thesis.

2.1 Characterizing Energy Use of Manufacturing Processes

Efforts have been undertaken over the past few decades to achieve the goal of environmentally responsible manufacturing, which has included the evaluation of energy consumption of advanced and conventional manufacturing processes.

For example, energy and material flow analysis in a binder-jetting process was performed by Meteyer et al. [17]. Their main aim was to estimate energy consumption in a metal binder jet process. The unit process modeling approach was undertaken to provide life cycle inventory (LCI) data for life cycle analysis (LCA) of the processes. Experimentation and data analysis was performed to determine correlations between process parameters and LCI data. The model was used to estimated energy consumption in the printing process with 98% accuracy. The authors concluded that energy data could aid in creating LCI for further LCA studies. Similarly, Baumers et al. [18] developed a combined model to estimate build time, energy consumption, and cost in material jetting process. Energy consumption could be estimated using the developed model with a mean average error of 15.31%. The proposed model to estimate build time accounts for the motion of the print head during material deposition. The build time model is compared for two deposition scenarios, one in which deposition time per layer is fixed and a second relating total build to deposition area per layer. The authors concluded that both scenarios produce significant estimation errors.

A mathematical model with an aim to evaluate energy consumption of a stereolithography (SLA) additive process was developed by Yang et al. [19]. The energy consumption model was developed by quantifying the energy contributors of each unit process of the mask image projection (MIP) SLA process. An experimental design and analysis approach was used to validate the developed model, explore potential interaction between process parameters, and optimize process parameters to minimize energy consumption. The response surface optimization technique was utilized to obtain optimal process parameters to minimize energy consumption. Optimization enabled greater than 50% reduction in energy consumption when compared to default working conditions. Sustainability analysis of the selective laser sintering additive process with energy as the metric was performed by Sreenivasan and Bourell [20]. Energy consumed by the entire process was evaluated by measuring energy consumption across various unit processes associated with laser sintering process. The novel contribution of the study was that the authors provided a factor, named energy indicator, to be used for process comparison.

Similar efforts have been undertaken to characterize energy consumption in subtractive processes, which can be used to support analysis of HASM processes. Diaz et al. [21] characterized specific energy consumption of a three-axis milling machine to study the effect of material removal rate on energy consumption. The authors reviewed strategies for characterizing and reducing energy consumption of milling machine tools during their use. The approach enables characterizing energy consumption as a function of process rate. The study showed that machining time dominates energy consumption. They extended the work by comparing the differences in machine power demand for cutting aluminum and polycarbonate workpieces.

From an optimization perspective, Yan and Li [22] developed a multi-objective optimization methodology with an aim to evaluate trade-offs between sustainability (cutting energy), production rate (material removal rate), and product quality (surface roughness) for a milling process. The resulting optimization methodology was based on weighted grey relational analysis, a quantitative method to determine weight factors of multiple unequal responses. The results obtained through application of the optimization methodology indicated that width of cut is the most influential parameter on process energy use; this result was validated using conventional experimental analysis (the Taguchi method).

Further, to provide a reliable estimation of energy consumption in a milling process under various machining conditions, Li et al [23] developed mathematical models based on thermal equilibrium and empirical modeling. The presented energy consumption model was a function of material removal rate and spindle speed. The developed model provided high level accuracy for estimating energy consumption. The models were validated on a number of milling processes under various material removal rates. Efforts to extend the validation of model with other factors is necessary, as noted in the future research.

Though the reported approaches in this section enable characterization of energy consumption of various manufacturing processes, a flexible representation of manufacturing processes, constraining their ability to consistently evaluate changes in environmental impacts due to modifications in individual manufacturing processes [4].

2.2 Unit Manufacturing Process Modeling

To address the need for uniform methods and software tools for characterizing manufacturing processes and systems, the ASTM International E60.13 subcommittee developed and published standard ASTM 3012-16 [16]. The standard provides a methodology for developing UMP models that manufacturing researchers and practitioners can use to quantify, assess, and improve the sustainability performance of manufacturing systems from the perspective of materials and energy use. As noted above, UMPs are the smallest elements in manufacturing that add value through transformation of shape, structure, or workpiece properties [24].

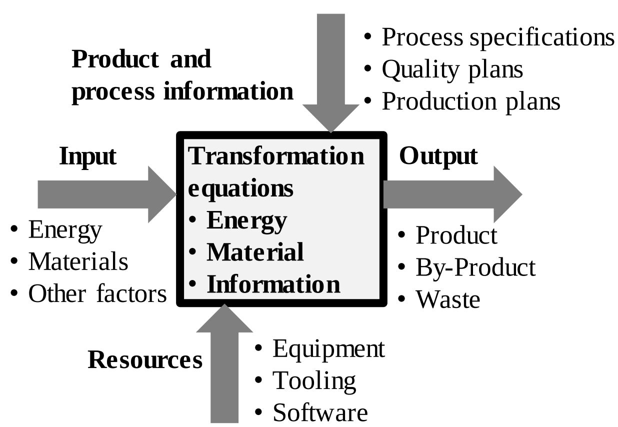

Figure 2.1: Unit manufacturing process (UMP) model representation (after [16])

UMP characterization in accordance with the ASTM standard enables deeper understanding of the process and can improve process-level decision making [25]. Further, composing UMP models can enhance manufacturing system-level understanding and improvement. While researchers have recently applied the ASTM 3012-16 standard to characterize environmental impacts of various individual manufacturing processes, the Unit Process Life Cycle Inventory (UPLCI) methodology [26,27] was one of the initial efforts reported for developing methods for unit manufacturing process characterization, prior to the development of the ASTM standard. The aim of the UPLCI approach was to enable formalization of a framework for inventory analysis of the manufacturing stage of the product life cycle. It was noted that dividing a manufacturing process into subprocess models enabled reliability and precision. The approach facilitated sustainability analysis of manufacturing systems by aggregating life cycle inventory data of UMPs unit manufacturing processes that comprised the manufacturing system.

In parallel with this initial work, a sustainability characterization methodology for UMPs was reported by Madan et al. [28] as a precursor to the ASTM standard. The developed methodology was applied to characterize energy consumption in injection molding, which involved selection and determination of process parameters, defining mold cavity details, selection of the injection molding machine, theoretical calculations for cycle time, and estimation of energy consumption. A structured information model, as currently contained in the ASTM standard, was not developed as part of their work, and thus, information flow across the design and manufacturing domains for the injection molding process application was restricted.

Doran et al. [29] developed an approach to compare the sustainability performance of additive and subtractive manufacturing processes based on UMP modeling. Their aim was to compare the economic, environmental, and social impacts of producing a functional part using direct energy deposition (additive process) with milling (subtractive process). Populating UMP metrics into a LCA life cycle assessment framework enabled the evaluation of sustainability impacts of both processes to determine which manufacturing method might be more appropriate during process planning based on selling price (economic), greenhouse gas emissions (environmental), and injuries per part (social). Their conclusions were limited by the material and process types investigated, and the resulting relationships (e.g., greenhouse gas emissions in relation to final part volume) were not validated against actual process data.

Building upon their prior work for injection molding, Mani et al. [30] applied the ASTM E3012-16 standard for sustainability characterization of additive manufacturing processes. The aim of this work was to provide a reference for the additive manufacturing community to benchmark additive processes on a sustainability basis. Their proposed methodology involved four steps: 1) understand process physics, 2) perform sustainability characterization, 3) benchmark sustainability performance of theoretical model against industry averages, and 4) plan for improving sustainability performance.

Recent work on applying the UPLCI methodology to characterize a grinding process was reported by Linke and Overcash [31]. The main aim of their work was to provide calculation tools to estimate energy use and mass loss of a unit manufacturing process. The methodology provided reusable models to analyze environmental impacts of grinding unit operations. Their analysis indicated that energy consumption, metal chips removed, and tool debris are the major contributors to environmental impacts in grinding. Extending the model and linking with other UPLCI to evaluate process flows is noted as future work. Similar effort was made by Zhang and Zhao to develop a UPLCI for gas metal arc welding (GMAW) process. The UPLCI methodology involved both the screen approach and the in-depth approach. Parameters affecting energy required for GMAW process was characterized. The developed model was demonstrated for joining two pieces of body panels in an automotive assembly shop.

Currently, researchers are not only developing models for various additive and subtractive UMPs based on the standard, but they are also developing methods and frameworks from a software perspective to enable reusability, composability, and extensibility of the models, as briefly explained in the next section.

2.3 Information Modeling of Manufacturing Process

The most common software applications for sustainability assessment are based on the life cycle assessment (LCA) methodology [32]. Though LCA tools can inform product designers and manufacturers about the environmental impacts of materials and part production, they do not facilitate in-depth, process-level analysis [25]. Thus, since they are limited in aiding sustainability evaluation of manufacturing processes, LCA-based applications are not well-suited for production planning [33]. To overcome these deficits of LCA software tools, product and process information for modeling production impacts, including complex sustainability information, must be organized in a structured manner in order to be used by emerging assessment methods and tools [34].

Information modeling is common in software engineering for building system architectures, and has recently gained popularity in the manufacturing domain [35]. It enables the organization of complex information, such that it can be easily implemented into a software application. Information modeling helps in defining concepts, relationships, rules, and operations to specify data semantics with regard to a domain [33]. Information modeling techniques used in recent manufacturing process modeling practice are based on entity relationships, functional modeling, and object-oriented approaches [36].

As alluded to above, manufacturing process analysis is a recognized need within the sustainable manufacturing research community [37]. As a result, efforts for integrating information modeling approaches with the development of UMP models in accordance with the ASTM 3012-16 standard have been reported. Madan et al. [38] developed a science-based guideline for predicting, benchmarking, and evaluating energy consumption in manufacturing processes. The developed guideline was applied to estimate energy consumption for an injection molding process. Next, they developed a Visual C# software application based on the guideline for predicting energy consumption of individual manufacturing processes with a focus on tool usability.

To evaluate alternative manufacturing process flows, Garretson et al. [39] developed a software application using MS Visual Basic to assess a set of sustainability metrics. The methodology was demonstrated for assessment of cradle-to-gate sustainability performance of metal aircraft components. It was shown that the approach could assist sustainable design and manufacturing decision making. However, the developed methodology did not support the comparison of the various sustainability metrics due to a lack of a standard metric weighting scheme. To extend the application of the standard, a methodology to facilitate systematic reuse of UMP models was developed by Shankar Raman et al. [25]. This is was achieved by encapsulating different aspects of complex processes into reusable building blocks. The methodology involved defining template UMP information models, which could be further abstracted and customized to represent an application specific, upgraded manufacturing process. A software application based on the methodology was not provided, but noted as a need for future research.

While the previous research investigated reusability of UMP models, Smullin et al. [40] and Zhang et al. [33] developed methods and applications to enable composability of UMP models. Smullin and co-workers aimed to realize an information modeling framework to assess the sustainability performance of manufacturing process flows. This goal was achieved by implementing an application architecture in Visual Basic comprised of a calculation engine, UMP warehouse, controller, and a graphical user interface. The developed application facilitated sustainability assessments of product manufacturing flows, but lacked a multi-criteria decision-making ability to compare sustainability metrics against each other. The goal of Zhang and co-workers was to develop an information model to capture and integrate information for sustainability evaluation of manufacturing processes. They proposed a process-oriented information model to achieve the goal and also developed a three-layer framework utilizing the proposed information model. An information model and software application was developed for the injection molding process, which was expanded from the proposed generic model. The operation of the proposed model and the three-layer framework was verified by assessing the sustainability impacts of manufacturing a gear part.

2.4 Cyclic Manufacturing

While manufacturers have undertaken efforts to characterize the sustainability performance of UMP from both process and system level, flexible and rapid manufacturing processes are gaining traction due to their suitability for the production of parts exhibiting complex geometries and the use of advanced materials [1]. Cyclic manufacturing processes enable flexible and rapid production of parts by repeating a physical sequence of subprocesses for each part feature, forming a manufacturing cycle with consistent or varying process parameter settings. Advanced manufacturing processes such as additive and hybrid manufacturing processes represent cyclic manufacturing processes. For example, subprocesses that describe the cyclic nature of a laser powder bed fusion additive process include spreading a layer of powder, melting the powder, and lowering the build platform for the next layer [11]. Existing research on cyclic manufacturing processes have focused on optimizing the data generated during production, since it delineates the dynamics of mechanistic conditions of the subprocesses in each cycle [9].

For example, Kozjek et al. [5] developed a data-driven methodology to extract information for identifying faulty conditions in a cyclic manufacturing process. Their methodology utilizes a two-phase data analysis work-flow: the first phase utilizes a decision tree heuristic algorithm to establish the rules for extracting process condition information and the second phase uses a clustering algorithm to identify the faulty conditions. The methodology was demonstrated to minimize the number of unplanned machine stops in plastic injection molding. Similarly, Febbraro et al. [41] modeled cyclic manufacturing processes using a deterministic time event graph to model process performance. They then applied a two-level multi-objective optimization procedure to maximize system throughput and minimize work-in-progress. The optimization approach aided in solving combinatorial issues due to flow optimization and operation sequencing. Their goal was to achieve formalization of the optimization problem and decomposition of the problem into tractable sub problems. While these studies point to the growing development and adoption of advanced cyclic manufacturing processes, limited work has been done to characterize their sustainability impacts, with no evidence of prior studies provided in research literature.

In recent years, advanced cyclic processes, termed hybrid manufacturing, are increasingly being recognized as a means to meet production goals, such as reducing equipment and space needs, and shortening processing, inspection, and handling times [12]. The key advantage of hybrid manufacturing is the ability to overcome the limitations of individual processes that cannot be otherwise eliminated due to process technology constraints. Hybrid manufacturing processes open up new opportunities and applications for fabricating components that cannot be produced efficiently by using currently available process technologies [13]. To provide a deeper understanding of hybrid processes, a collaborative working group of the International Academy for Production Engineering (CIRP) dealing with hybrid processes provided descriptive definitions [42]:

- Open definition: *A hybrid manufacturing process combines two or more established manufacturing processes into a new combined set-up whereby the advantages of each discrete process can be exploited synergistically.*
- Narrow definition: *Hybrid processes comprise a simultaneous acting of different (chemical, physical, controlled) processing principles on the processing zone.*

In the context of the research presented herein, a hybrid process is a synergistic combination of an additive and a subtractive process in a single machine for improving part quality and part functionality, along with productivity [14]. This approach has been termed *hybrid additive subtractive manufacturing* (HASM), and can involve sequential (additive to subtractive) or iterative (a series of additive and subtractive) process steps. Hybrid processes require novel approaches to fixturing and orientation to fabricate a part, as well as process integration and process planning aspects, which have been explored in prior research as highlighted below.

Process integration studies relevant to HASM processes provide knowledge on mechanical, electrical, and software integration for various combinations of additive and subtractive processes. For example, details on the mechanical and software integration for a five-axis hybrid manufacturing system, known as Laser Additive Manufacturing Process (LAMP), was provided by Nagel et al. [8]. The LAMP system aimed to increase build-size capability, and improve the accuracy and surface finish of metal structures with minimal post-processing. This aim was achieved by integrating a five-axis CNC machine with laser metal deposition system. The developed LAMP system enabled production of functional metal parts with desired surface finish and tolerance, along with increased productivity, repeatability, and safety.

Similarly, Karunakaran et al. [43] described the mechanical, electrical, and software integration of the Arc Hybrid Layered Manufacturing (ArcHLM) hybrid system. This system was developed to achieve both near net shape metal deposition and finish machining on the same machine. The approach to achieve the aim was to retrofit arc welding unit components on a CNC mill at a low cost. The ArcHLM process reduced cycle time by 37.5% and cost by 23%, relative to a conventional CNC route. While these two studies focused on metal parts, Lee et al. [12] provided details on development of a polymer-based hybrid manufacturing system to produce polymer parts without support structures. The developed system involves the integration of a five-axis CNC machine with fused deposition modeling process components. The system was used to demonstrate the printing of polymer around embedded metal supports to increase overall part strength.

Prior research has also investigated the efficient use of hybrid processes in production by considering their influence on microplanning and macroplanning activities, including automated process planning and tool path generation for HASM processes. Ren et al. [44] developed an integrated process planning framework with an aim to automate the hybrid manufacturing process. Using their process planning software, they demonstrated automated fabrication of functional parts by combining laser deposition and machining within a single setup. The proposed framework involved CAD model decomposition, toolpath generation, and a collision detection algorithm. Experiments were conducted to validate the feasibility of the framework. Nau et al. [45] provided an approach for hybrid process development and also demonstrated a general approach for risk and potential analysis for hybrid manufacturing technologies to aid process integration decision making. The main aim of their work was to propose a method for detecting, evaluating, and implementing hybrid processes into existing production environments.

Ruan et al. [46] developed an algorithm for adaptive multi-axis slicing for a five-axis laser-aided manufacturing process. The adaptive slicing was based on local geometry and build direction, and was able to generate uniform and non-uniform thickness slices. The algorithm enables a hybrid system to build parts more efficiently by reducing almost 50% of the support structures. In support of production studies, mechanical and material characterization has provided knowledge about the performance of components manufactured using HASM processes. One such study includes that of Du et al. [47] in which microstructure and hardness variations in an 18Ni maraging steel part fabricated using a HASM process (combining selective laser melting and milling) was compared with an additive manufacturing process (selective laser melting). They found that the parts fabricated using the HASM process exhibited a higher density and hardness.

With the growing development and adoption of advanced cyclic manufacturing processes, it is critical to understand the mechanistic behavior of each subprocess to accurately quantify and continuously improve process performance metrics [9]. Though existing literature has shown that cyclic manufacturing processes are promising alternatives to sequential manufacturing [45], there is a dearth of methods reported that enable the systematic characterization of sustainability performance of cyclic manufacturing processes. Sustainability characterization of cyclic manufacturing is a challenge due to the complex, integrated nature of subprocesses, which require a higher level of information synthesis than individual processes [9].

From the presented literature, we conclude the following:

- Limited work has been done to characterize energy consumption of cyclic manufacturing process, with no prior studies reported in research literature.
- A uniform methodology for evaluating the sustainability performance of cyclic manufacturing process has not been reported, possibly due to the complex, integrated nature of subprocesses, which require a higher level of information synthesis than individual, or unit, processes.
- While product and process information modeling concepts have been incorporated into a published ASTM standard, prior reported information modeling methods, frameworks, and applications lack a approach for constructing individual UMP models, composing multiple UMP models having a cyclic nature, and assessing sustainability performance metrics for composed UMP models representing a cyclic process using a unified software framework.
- There is a dearth of methods to evaluate the effectiveness of models developed based on the ASTM standard for characterizing the environmental impacts of manufacturing processes.

Characterizing the Sustainability Performance of Cyclic Manufacturing Process: A Hybrid Manufacturing Case

by
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CHAPTER 3. CHARACTERIZING THE SUSTAINABILITY PERFORMANCE OF CYCLIC MANUFACTRING PROCESSES: A HYBRID MANUFACTURING CASE

3.1 Abstract

The drive for ever-increasing materials and energy efficiency and associated cost savings has compelled manufacturers to adopt flexible and rapid production systems. The technical limitations and sustainability concerns of conventional unit processes and sequential process flows have led to widespread adoption of advanced manufacturing processes that exhibit cyclic nature, termed cyclic manufacturing processes. While cyclic manufacturing processes enable efficient production through reduced time-to-market, lower production costs, and shorter manufacturing process chains, relatively little attention has been paid toward characterizing their associated environmental, economic, and social impacts. A manufacturing process modeling framework is developed to support sustainability performance characterization of cyclic manufacturing processes. The developed framework enables model reusability, extensibility, and composability to characterize, assess, and extract product and process sustainability information. It is applied to characterize environmental impacts of a low-cost, hybrid (additive-subtractive) process for production of polylactide (PLA) parts, and compared with a conventional subtractive process (milling).

3.2 Introduction

In recent years, addressing sustainability impacts due to energy consumption of manufacturing processes has become an unprecedented global priority [33]. According to the U.S. Energy Information Administration [48], manufacturing accounts for 66% of industrial energy consumption in the United States; the industrial sector accounts for 32% of U.S. energy consumption. While extraction of energy resources can have a detrimental impact on the environment, conversion of these feedstocks into energy results in the generation of greenhouse gases, which have been linked to climate change [6]. Continual reduction of process energy consumption through increased manufacturing efficiency is being pursued to strengthen the economic vitality of U.S. manufacturers, while also helping to protect our environment [1]. Reducing sustainability impacts of industrial energy consumption requires manufacturers to characterize and document process energy use, leading to improved economic and environmental performance of their operations [4].

While manufacturers have undertaken efforts to characterize the sustainability performance of unit manufacturing processes (UMP), flexible and rapid manufacturing processes are gaining traction due to their suitability for the production of parts exhibiting complex geometries and the use of advanced materials [1]. In particular, conventional unit processes and traditional sequential process flows limit the manufacturability of state-of-the-art products in aerospace, biomedical, and chemical industries [45]. Manufacturing technology research has focused on developing additive and hybrid processes, which exhibit a cyclic nature and enable flexible and rapid production, effectively shortening the time-to-market, decreasing the manufacturing process chain, and reducing production costs [8]. These processes have been termed cyclic manufacturing processes, and defined as "a manufacturing process in which the parts are produced repeating a sequence of subprocesses that forms the manufacturing cycle" [9]. With the growing development and adoption of advanced cyclic manufacturing processes, it is critical to understand the mechanistic behavior of each subprocess to accurately quantify and continuously improve process performance metrics [9]. Though existing literature has shown that cyclic manufacturing processes are promising alternatives to sequential manufacturing [45], there is a dearth of methods reported that enable the systematic characterization of sustainability performance of cyclic manufacturing processes. Sustainability characterization of cyclic manufacturing is a challenge due to the complex, integrated nature of subprocesses, which require a higher level of information synthesis than individual processes [9].

The objective of the research herein is to facilitate sustainability performance characterization of cyclic manufacturing processes by developing a manufacturing process modeling framework. This framework will enable characterization, assessment, and extraction of product and process sustainability information through model reusability, extensibility, and composability. Achieving this objective will aid developers and users of cyclic manufacturing processes to incorporate broader sustainability considerations into their decision-making during process development, product design, and process planning activities. The developed manufacturing process modeling framework is utilized to characterize a hybrid manufacturing process for evaluating and comparing its environmental performance with a conventional unit manufacturing process (milling) for fabricating products with varying complexities. The remainder of the paper is organized into four sections. Section 2 presents the background, and discusses characterization of energy use in manufacturing processes, UMP modeling, and cyclic and hybrid manufacturing processes. Next, Section 3 describes the manufacturing process modeling framework developed in this research. In Section 4, the framework is demonstrated for a hybrid manufacturing process. Finally, Section 5 discusses the implications of this research and presents opportunities for future research.

3.3 Background

The research herein is driven by the following rationale: (1) environmentally responsible manufacturing can be aided through process energy characterization, (2) a uniform methodology for characterizing energy use can be devised through a UMP modeling approach, and (3) flexible and rapid production can be enabled through cyclic manufacturing processes. This section briefly discusses the existing literature supporting this rationale.

3.3.1 Characterizing Energy Use of Manufacturing Processes

Efforts have been undertaken over the past few decades to achieve the goal of environmentally responsible manufacturing, which has included the evaluation of energy consumption of advanced and conventional manufacturing processes. For example, energy and material flow analysis was performed by Meteyer et al. [49] to estimate energy consumption in a metal binder jet process. They applied the UMP modeling approach to provide life cycle inventory (LCI) data for life cycle analysis (LCA) of the subprocesses. In a similar manner, a mathematical model was developed by Yang et al. [19] with an aim to evaluate energy consumption of a stereolithography (SLA) additive process. The energy consumption model was developed by quantifying the energy contributors of each subprocess of the mask image projection (MIP) SLA process. Similarly, Baumers et al. [18] developed a combined model to estimate build time, energy consumption, and cost in material jetting process. Energy consumption could be estimated using the developed model with a mean average error of 15.31%. The proposed model to estimate build time accounts for the motion of the print head during material deposition. The build time model is compared for two deposition scenarios, one in which deposition time per layer is fixed and a second relating total build to deposition area per layer. The authors concluded that both scenarios produce significant estimation errors.

Many similar approaches have been reported for subtractive manufacturing processes. For example, Diaz et al. [21] characterized the specific energy consumption of milling to study the effect of material removal rate on energy consumption. The authors reviewed strategies for characterizing and reducing energy consumption of milling machine tools during their use. Further, to provide a reliable estimation of energy consumption in a milling process under various machining conditions, Li et al [23] developed mathematical models based on thermal equilibrium and empirical modeling. The presented energy consumption model was a function of material removal rate and spindle speed. The models were validated on a number of milling processes under various material removal rates.

3.3.2 Unit Manufacturing Process Modeling

To address the need for uniform methods and software tools for characterizing manufacturing processes and systems, the ASTM International E60.13 subcommittee developed and published standard ASTM 3012-16 [16]. The standard provides a methodology for developing UMP models (Fig. 3.1) that manufacturing researchers and practitioners can use to quantify, assess, and improve the sustainability performance of manufacturing systems from the perspective of materials and energy use.

As noted above, UMPs are the smallest elements in manufacturing that add value through transformation of shape, structure, or workpiece properties [24]. UMP characterization in accordance with the ASTM standard enables deeper understanding of the process and can improve process-level decision making [25]. Researchers have recently applied the ASTM 3012-16 standard to characterize environmental impacts of various individual manufacturing processes.

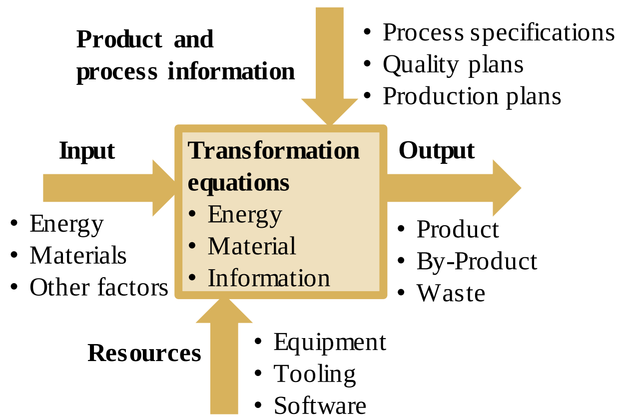

Figure 3.1: Unit manufacturing process (UMP) model representation (after [16])

A sustainability characterization methodology for UMPs was reported by Madan et al. [28], as a precursor to the ASTM standard. The developed methodology was applied to characterize energy consumption in injection molding, which involved selection and determination of process parameters, defining mold cavity details, selection of the injection molding machine, theoretical calculations for cycle time, and estimation of energy consumption. Doran et al. [29] developed an approach to compare the sustainability performance of additive and subtractive manufacturing processes based on UMP modeling. Their main aim was to compare the economic, environmental, and social impacts of producing a functional part using direct energy deposition (additive process) with milling (subtractive process). Mani et al. [30] applied the ASTM E3012-16 standard to develop a methodology for sustainability characterization of additive manufacturing processes. The aim of their work was to provide a reference for the additive manufacturing community to benchmark additive processes on a sustainability basis. Recent work on applying UPLCI methodology to characterize a grinding process was reported by Linke and Overcash [31]. The main aim of their work was to provide calculation tools to estimate energy use and mass loss of a unit manufacturing process. The methodology provided reusable models to analyze environmental impacts of grinding unit operations. The results based on the analysis indicated that energy consumption, metal chips removed, and tool debris are the major contributors to environmental impacts in grinding. Extending the model and linking with other UPLCI to evaluate process flows is noted as future work.

3.3.3 Cyclic Manufacturing

Cyclic manufacturing processes enable flexible and rapid production of parts by repeating a physical sequence of subprocesses for each part feature, forming a manufacturing cycle with consistent or varying process parameter settings. Advanced manufacturing processes such as additive and hybrid manufacturing processes represent cyclic manufacturing processes. For example, subprocesses that describe the cyclic nature of a laser powder bed fusion additive process include spreading a layer of powder, melting the powder, and lowering the build platform for the next layer [11]. Existing research on cyclic manufacturing processes have focused on optimizing the data generated during production, since it delineates the dynamics of mechanistic conditions of the subprocesses in each cycle [9].

For example, Kozjek et al. [5] developed a data-driven methodology to extract information for identifying faulty conditions in a cyclic manufacturing process. Their methodology utilizes a two-phase data analysis work-flow: the first phase utilizes a decision tree heuristic algorithm to establish the rules for extracting process condition information and the second phase uses a clustering algorithm to identify the faulty conditions. The methodology was demonstrated to minimize the number of unplanned machine stops in plastic injection molding. Similarly, Febbraro et al. [41] modeled cyclic manufacturing processes using a deterministic time event graph to model process performance. They then applied a two-level multi-objective optimization procedure to maximize system throughput and minimize work-in-progress. The optimization approach aided in solving combinatorial issues due to flow optimization and operation sequencing. Their goal was to achieve formalization of the optimization problem and decomposition of the problem into tractable sub problems. While these studies point to the growing development and adoption of advanced cyclic manufacturing processes, limited work has been done to characterize their sustainability impacts, with no evidence of prior studies provided in research literature.

In recent years, advanced cyclic processes, termed hybrid manufacturing, are increasingly being recognized as a means to meet production goals, such as reducing equipment and space needs, and shortening processing, inspection, and handling times [12]. According to Zhu et al. [13], hybrid manufacturing processes open up new opportunities and applications for manufacturing various components, which cannot be produced efficiently using standalone processes. In the context of the research presented herein, a hybrid process is a synergistic combination of an additive and a subtractive process exhibiting a cyclic nature in a single machine for improving part quality, part functionality, and manufacturing productivity [14]. Existing research provides extensive knowledge on hybrid manufacturing process integration and process planning.

Process integration studies relevant to hybrid processes provide knowledge on mechanical, electrical, and software integration for various combinations of additive and subtractive processes. For example, details on the mechanical and software integration for a five-axis hybrid manufacturing system, known as LAMP, was provided by Nagel et al. [8]. The LAMP system aimed to increase build-size capability, and improve the accuracy and surface finish of metal structures with minimal post-processing. This aim was achieved by integrating a five-axis CNC machine with laser metal deposition system. The developed LAMP system enabled production of functional metal parts with desired surface finish and tolerance, along with increased productivity, repeatability, and safety.

Prior research also investigated the efficient use of hybrid processes in production by considering their influence on microplanning and macroplanning activities, including automated process planning and tool path generation for hybrid processes. Ren et al. [44], for example, developed an integrated process planning framework with an aim to automate the hybrid manufacturing process. Using process planning software developed based on the framework, they demonstrated automated fabrication of functional parts by combining laser deposition and machining within a single setup. The proposed framework involved CAD model decomposition, toolpath generation, and a collision detection algorithm. Experiments were conducted to validate the feasibility of the framework.

While prior work has been conducted to understand the performance of integrated processes and process planning for hybrid processes, no studies have been reported that investigate the energy, materials, or cost impacts of using hybrid processes in production environments. The work herein attempts to address this deficit and is explained in the following sections.

3.4 Manufacturing Process Modeling Framework

This section describes the manufacturing process modeling framework developed for characterizing, assessing, and extracting environmental impact information of cyclic manufacturing processes. The scope of this study is exclusive to characterizing two subprocesses (modeled as UMPs) and subsequently aggregating the performance metrics for the associated cyclic manufacturing process (Fig. 3.2); the framework can be applied for multiple subprocesses in a similar manner. Since the utility of a cyclic manufacturing process is its ability to alternate between subprocesses on a single machine, accommodating multiple cycles and cycle variants, the conception of a cyclic UMP model was necessary in order to accurately track sustainability metrics of each subprocess.

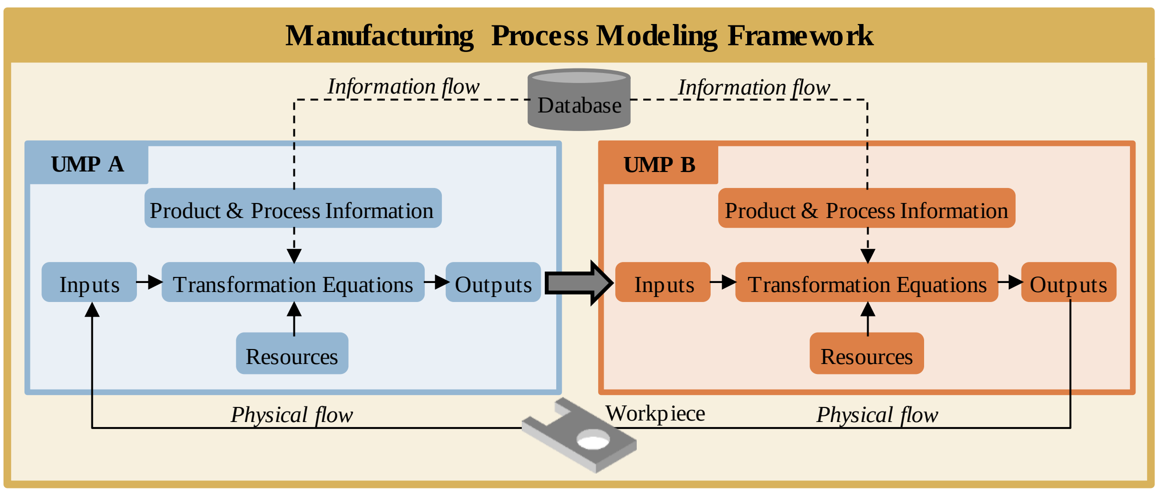

Figure 3.2: Manufacturing process modeling framework for characterizing and assessing the sustainability performance of cyclic manufacturing processes

This conceptual model for aggregating sustainability metrics of cyclic processes is designed to enable reversal of the process flow direction, e.g., to accommodate both UMP A-to-UMP B and UMP B-to-UMP A flows. With regard to material flow (or physical part movement), the physical output of the first UMP becomes a physical input to the subsequent UMP. To illustrate this point, consider a part that requires partial fabrication via UMP A, followed by UMP B. In fact, parts produced using cyclic processes often require multiple cycles in this manner. Throughout the extent of these cycles, there is a continual stream of product and process information being stored and exchanged between both of the UMP models forming the cyclic model. This information flow facilitates the process of tracking and aggregating sustainability metrics for a cyclic manufacturing process using composed UMP models under the ASTM standard.

Product information includes information such as part volume, part geometry, and part height, required for evaluation of the relevant manufacturing process. Process information includes control parameters, fixed parameters, intermediate variables, linking variables, and metrics of interest [16]. Control parameters are tunable parameters that can be adjusted to evaluate different process settings, such as depth of cut and spindle speed in a computer numerical controlled (CNC) milling operation. Fixed parameters include parameters set through the evaluation of transformation equations (describes the relation between inputs and outputs) e.g., specific heat capacity of a filament extruder. Intermediate variables are calculated variables required to complete evaluation of the transformation equations, e.g., machining time is calculated to determine machining energy use. Linking variables and metrics of interest are the two pieces of information that need to be exchanged between the two UMPs. Linking variables can include any of the prior mentioned product or process information. Metrics of interest include UMP performance metrics, e.g., energy consumed or cost per part.

Product and process information for each cycle ($\boldsymbol{C}_i$) in a collection of cycles $\{\boldsymbol{C}_{1,}\boldsymbol{C}_{2,}\boldsymbol{C}_{3,} \dots \boldsymbol{C}_N\}$ can be defined and stored according to the following elements: subprocess ($\boldsymbol{C}_i^{subproc}$), product data ($\boldsymbol{C}_i^{prod}$), control parameters ($\boldsymbol{C}_i^{contpara}$), fixed parameters ($\boldsymbol{C}_i^{fixpara}$), intermediate variables ($\boldsymbol{C}_i^{intervar}$), linking variables ($\boldsymbol{C}_i^{linkvar}$), and metrics of interest ($\boldsymbol{C}_i^{metrics}$). This information can be represented by an array (Eq.3.1), as

$$\boldsymbol{C}_i = \{\boldsymbol{C}_i^{subproc}, \boldsymbol{C}_i^{prod}, \boldsymbol{C}_i^{contpara}, \boldsymbol{C}_i^{fixpara}, \boldsymbol{C}_i^{intervar}, \boldsymbol{C}_i^{linkvar}\ \boldsymbol{C}_i^{metrics}\} \tag{3.1}$$

$$\forall\ i \in [1, N]: \boldsymbol{C}_i^{subproc}\ \in \{subproc\ 1, subproc\ 2\} \tag{3.2}$$

Eq. 2 asserts that $\boldsymbol{C}_i^{subproc}$ is an element of the set $\{subproc\ 1, subproc\ 2\}$ and it is true for all N cycles. Each element in Eq. 1 can be further defined by product feature number ($c_i^{feature}$), name of the data for identification (c_i^{name}), symbol representation of the data for use in mathematical representation (c_i^{symbol}), unit of the data defined by a standard measurement system (c_i^{unit}), valid bounds of the data (c_i^{bound}), and mathematical value of the data (c_i^{value}) when evaluated for a particular product and process scenario. This information can further be represented by Eqs. 3.3-3.8:

$$\boldsymbol{C}_i^{product} = \{p\boldsymbol{C}_i^{subproc},\ pc_i^{feature}, pc_i^{name}, pc_i^{symbol}, pc_i^{unit}, pc_i^{bound}, pc_i^{value}\} \tag{3.3}$$

$$\boldsymbol{C}_i^{contpara} = \{cp\boldsymbol{C}_i^{subproc}, cpc_i^{feature},\ cpc_i^{name}, cpc_i^{symbol}, cpc_i^{unit}, cpc_i^{bound}, cpc_i^{value}\} \tag{3.4}$$

$$\boldsymbol{C}_i^{fixpara} = \{fp\boldsymbol{C}_i^{subproc}, fpc_i^{feature}, fpc_i^{name}, fpc_i^{symbol}, fpc_i^{unit}, fpc_i^{bound}, fpc_i^{value}\} \tag{3.5}$$

$$\boldsymbol{C}_i^{intervar} = \{iv\boldsymbol{C}_i^{subproc}, ivc_i^{feature}, ivc_i^{name}, ivc_i^{symbol}, ivc_i^{unit}, ivc_i^{bound}, ivc_i^{value}\} \tag{3.6}$$

$$\boldsymbol{C}_i^{linkvar} = \{lv\boldsymbol{C}_i^{subproc}, lvc_i^{feature}, lvc_i^{name}, lvc_i^{symbol}, lvc_i^{unit}, lvc_i^{bound}, lvc_i^{value}\} \tag{3.7}$$

$$\boldsymbol{C}_i^{metrics} = \{m\boldsymbol{C}_i^{subproc}, mc_i^{feature}\ mc_i^{name}, mc_i^{symbol}, mc_i^{unit}, mc_i^{bound}, mc_i^{value}\} \tag{3.8}$$

In the foregoing equations, p is product data, cp is control parameter, fp is fixed parameter, iv is intermediate variable, lv is linking variable, and m is metric of interest. Equation 3.3 is a subarray for defining product information. Elements of the subarray are described below and also apply for Eqs. 3.4-3.8:

- $p\boldsymbol{C}_i^{subproc}$ defines the subprocess (e.g., milling) used to fabricate product p.
- $pc_i^{feature}$defines the feature (e.g., slot) of product p fabricated using $p\boldsymbol{C}_i^{subproc}$.
- pc_i^{name} defines the product information name (e.g., volume) of $pc_i^{feature}$.
- pc_i^{symbol} defines the notation (e.g., vol) of the pc_i^{name}.
- pc_i^{unit} defines the unit (e.g., mm^3) for pc_i^{name}.
- pc_i^{bound} defines the bounds for pc_i^{name}.
- pc_i^{value} defines the value of pc_i^{name}.

Figure 3.3 depicts the UMP quantification and aggregation algorithm developed and used in our work to store and evaluate information about the sustainability metrics of interest for cyclic manufacturing processes. It starts with defining the sequence of UMPs for one cycle and the total number of cycles using that sequence. Metrics for each cycle are quantified and stored in a database until the final cycle is completed. Once the final cycle in the set of sequences is completed, the stored information is extracted and aggregated using for-next loops to quantify the set of metrics for the entire process. Quantification and aggregation of metrics can be represented by Eq. 3.9.

$$M_C = \sum\{\left(m_{cycle_1}^{subproc_1} + m_{cycle_1}^{subproc_2}\right) + \left(m_{cycle_2}^{subproc_1} + m_{cycle_2}^{subproc_2}\right) + \cdots \left(m_{cycle\_N}^{subproc\_1} + m_{cycle\_N}^{subproc\_2}\right)\} \quad (3.9)$$

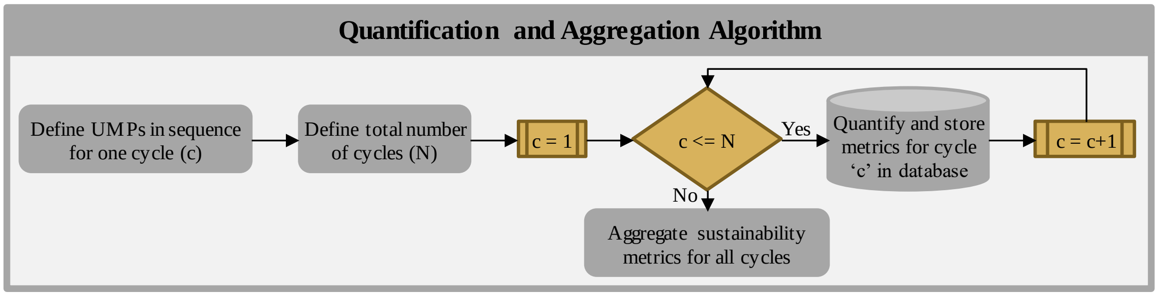

Figure 3.3: Algorithm for quantifying and aggregating sustainability performance metrics for cyclic manufacturing processes

The cyclic UMP model algorithm enables extraction and assessment of sustainability performance information for each subprocess and cycle. While an intuitive extension of the ASTM modeling framework, no UMP modeling approach has been reported to facilitate the tracking of metrics for cyclic processes in this way, nor has a corresponding information modeling approach been proposed that builds upon the current ASTM standard to facilitate application of the framework. Ongoing work is pursuing such an approach, and will be reported in a later publication.

3.5 Demonstration of the Framework

To demonstrate the functionality of the framework, it is utilized to characterize environmental impacts of a hybrid manufacturing process developed in-house at Oregon State University. First, the design and development of the hybrid manufacturing process is explained. Second, the hybrid manufacturing process model developed in this research is discussed. Third, the developed model is utilized to evaluate fabrication of polylactic (PLA) products with varying complexities. The metrics of interest for evaluating the environmental impacts include process energy use, CO_2 equivalent emissions, and process waste. The hybrid manufacturing metrics are compared with CNC milling (subtractive) process metrics. Additive manufacturing as a distinct UMP is not considered for comparison because the tolerance and surface finish specifications of the finished product produced are not achievable through an additive process alone. Last, the predicted hybrid process energy is experimentally validated using an energy monitoring system.

3.5.1 Hybrid Manufacturing Process

In the context of the research here, the hybrid manufacturing process is a synergistic combination of an additive process and a subtractive process on a single machine to fabricate a part and more effectively meet production requirements (e.g., part accuracy, surface finish, or improved environmental performance). ASTM International Committee F42 [27] defines additive manufacturing as *the process of joining material to make objects from three-dimensional (3D) model data, usually layer by layer, as opposed to subtractive manufacturing methodologies*. Fused filament fabrication (FFF) is a prominent material extrusion AM process in which fused material is drawn through a nozzle using a torque and pinch system, where it is heated and then deposited layer-by-layer [51]. The main advantages of this technology include: availability of a wide variety of materials, easy material change, quick production of thin parts, nontoxic material, and low temperature operation [52]. However, the accuracy and precision of parts printed using FFF is often uncertain due to the shrinkage and the internal stresses incurred during the process.

On the other hand, subtractive manufacturing is a material removal process in which the product is fabricated by cutting a workpiece to a final desired geometry. Computer numerically controlled (CNC) machines produce parts with low surface roughness and high geometric accuracies [53]. They possess a high degree of precision and repeatability and are capable of processing a wide variety of materials [54]. Compared to additive manufacturing, subtractive manufacturing can produce parts with good surface finish and high production throughput, but it has its limitations in terms of material consumption and design complexity. According to Zhu et al. [13], hybrid manufacturing processes open up new opportunities and applications for manufacturing various components, which cannot be produced efficiently by standalone processes. The combination of CNC machining and additive manufacturing provides a new and substantial solution to the limitations of additive processes due to higher accuracy and throughput that machining processes offer [55].

Our approach to develop a low-cost hybrid manufacturing process combines FFF (polymer-based additive) and CNC milling (subtractive process), by utilizing low-cost retrofits for 3D printing on a CNC milling machine. These integrated subprocesses have the ability to produce near netshape parts directly from a CAD representation using FFF and to post-process the parts using CNC milling to achieve acceptable surface finish in a single setup. Melted polymer is extruded through an extruder head, which acts as a tool to the CNC mill and takes advantage of its Z-direction motion controller. A schematic of the hybrid manufacturing process is shown in Fig. 3.4.

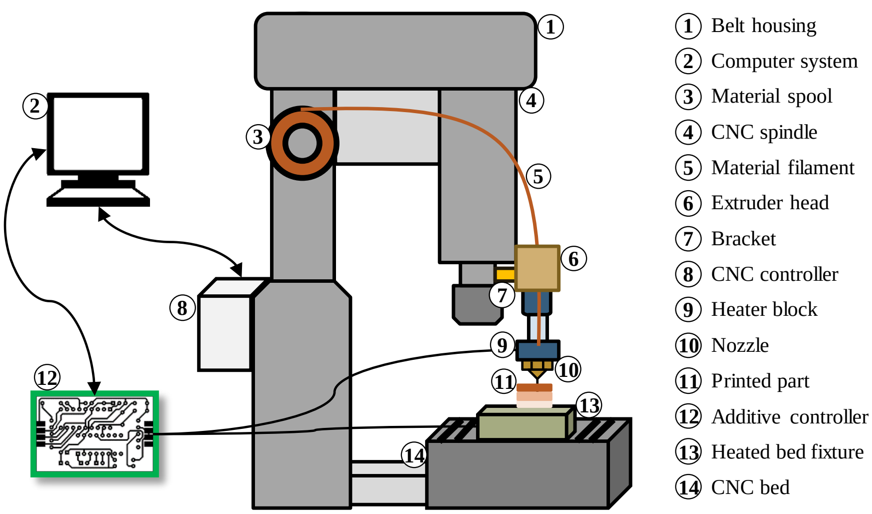

Figure 3.4: Schematic representation of the hybrid manufacturing process

The main manufacturing process of this hybrid system is the FFF process. Material is extruded layer-by-layer onto a heated bed, which is fastened to mill table as a fixture to coincide with the X and Y motion control of the CNC machine. The motion for both the extruder head and milling cutter is accomplished using the table driver motors of the CNC milling machine, which are controlled using a single CNC program. Control of the extrusion process is accomplished using a RAMBo v1.3 controller board, which is a low-cost 3D printer controller to execute extrusion and motion control commands based on the desired build paths and temperature feedback. In this setup, only the extrusion and heated bed functions are used; both are on/off control. Post-processing of the 3D print is done through a CNC milling operation using an endmill.

3.5.2 Hybrid Manufacturing Process Model

The developed hybrid manufacturing process was discussed in the previous section. This section describes the hybrid manufacturing process model developed based on the manufacturing process modeling framework (Section 3). Since the purpose of the hybrid manufacturing process is to fabricate polymer parts with good surface finish and productivity using a single setup, only one cycle is considered in this study. Eight transformation equations for the FFF subprocess are represented in the FFF UMP model shown in the top of Fig. 3.5. The total FFF processing time is a summation of idle time and deposition time for each layer, along with the setup time, which is comprised of time to heat the bed and nozzle. The deposition time for one layer is multiplied by the infill density, which depends on road width and gaps between adjacent roads, to account for infill percentages below 100% (maximum layer density).

Printing speed is substituted with feed rate of the CNC mill and acts as one of the main linking variables. The transformation equations for total FFF energy includes energy consumed by the bed and extruder head heaters, the driver motors to provide motion in the X, Y, and Z directions, and the extruder motor, along with setup energy (energy required to heat the bed and nozzle). Metrics for the subtractive subprocess of the hybrid process is represented in the transformation equations of the CNC milling UMP model (bottom of Fig. 3.5) [56]. Subtractive subprocess times include milling time, handling time, approach/retract time, and tool loading/unloading time. The volume of material removed, V_r (volume of waste), depends on the mass printed during the additive subprocess and material density (ρ_{mat}), which act as linking variables. Milling time is calculated by dividing the volume of material removed by the material removal rate. For each UMP (subprocess), aggregate metrics are used to evaluate process energy (E_c), CO_2 equivalent emissions (CO_{2_C}, and material waste (Mat_c) for the hybrid manufacturing process (Eqs. 3.10-3.12).

$$E_C = \sum\{\left(e_1^{FFF} + e_1^{CNC\ mill}\right)\} \tag{3.10}$$

$$CO_{2\_C} = \sum\{\left(CO_{2_1}^{FFF} + CO_{2_1}^{CNC\ mill}\right)\} \tag{3.11}$$

$$Mat_C = \sum\{\left(mat_1^{FFF} + mat_1^{CNC\ mill}\right)\} \tag{3.12}$$

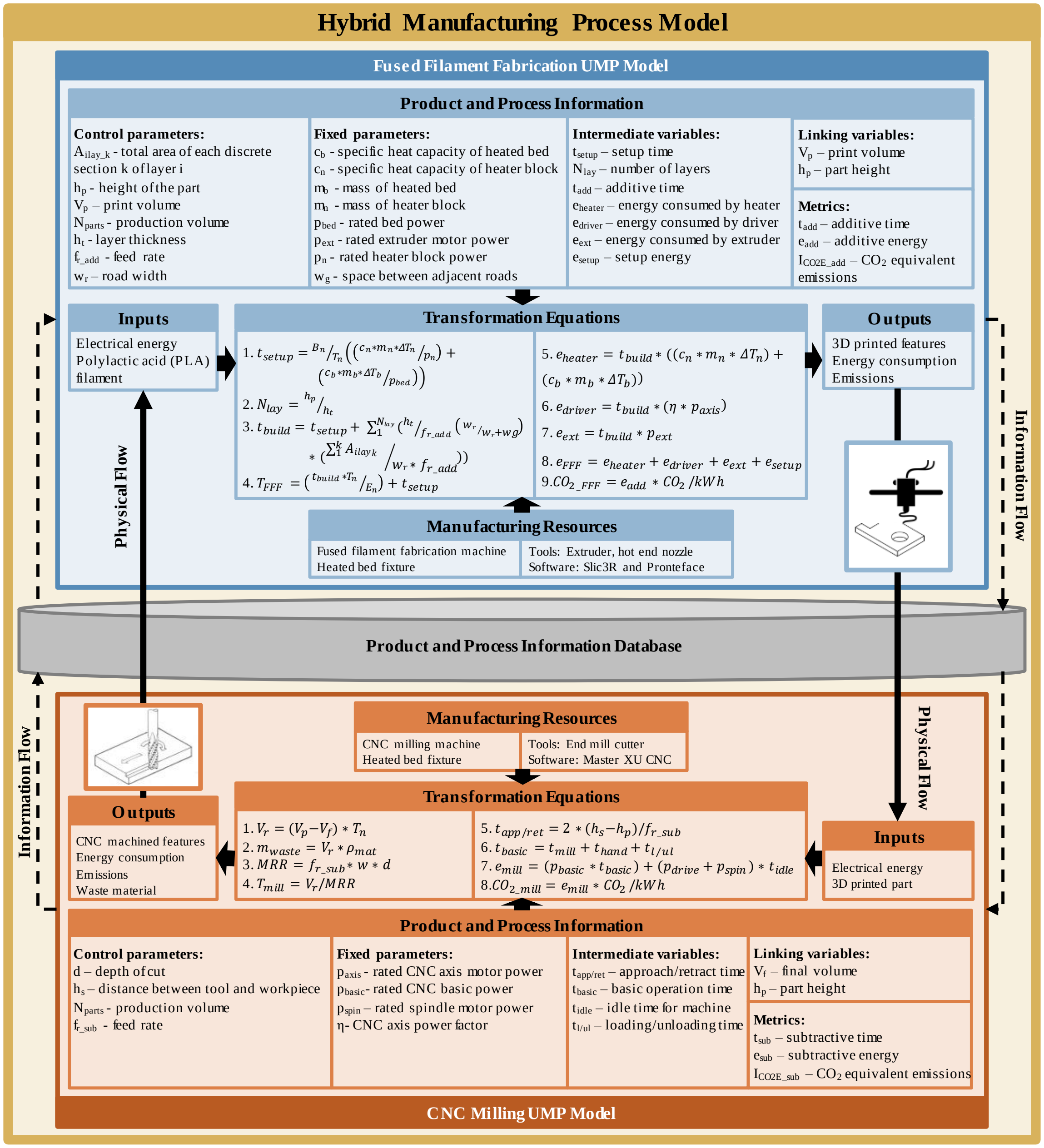

Figure 3.5: Hybrid manufacturing process model based on the manufacturing process modeling framework

3.5.3 Evaluation of the Hybrid Manufacturing Process Model

The hybrid manufacturing process model developed in Section 4.1 is utilized to evaluate and compare the environmental performance of the hybrid manufacturing process with a conventional unit manufacturing process – in this case, only milling is considered as an alternative, since FFF would not be able to achieve an acceptable surface finish. In addition, the effect of complexity on the selected performance metrics is explored for a set of parts with increasing complexity (Fig. 3.6). Here, we define complexity as part surface area to volume ratio (SA/V).

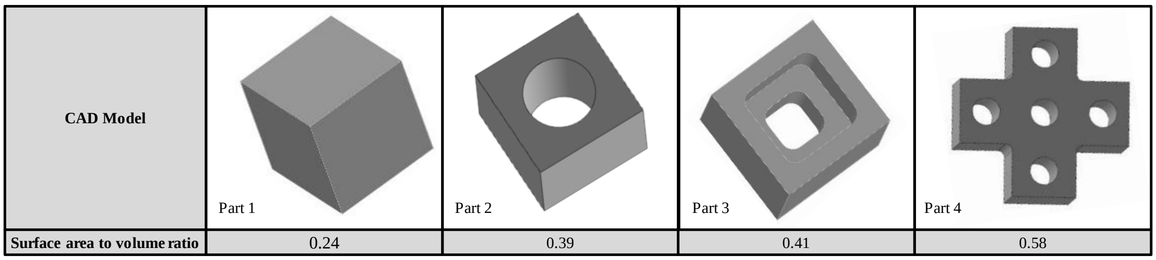

Figure 3.6: CAD models of products with varying complexity

Figure 3.7 displays total process energy, material waste, and CO_2 equivalent emissions for the four selected parts, which were determined using the developed hybrid manufacturing process model and compared with experimental results. It can be noted that the average energy consumption and associated carbon emissions for milling are approximately double than for the hybrid process. The waste material generated in milling ranges from 2-20 times more than produced during hybrid operations. Waste material generated during hybrid processing is correlated with the surface area of the part, while the volume of material waste from subtractive operations is based on the part volume and bounding box volume. Our focus on UMPs does not allow us to elucidate the environmental impacts of material extraction and processing, which would result in an even greater impact of milling for more complex parts.

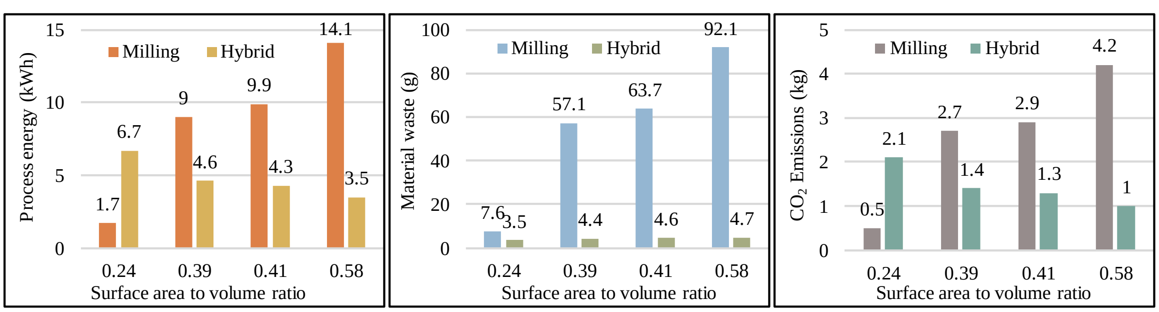

Figure 3.7: Environmental performance assessment of hybrid and milling processes for Parts 1-4

Thus, it is found that Part 2, Part 3, and Part 4 for example, produce relatively similar masses of waste (4.4-4.7g) when manufactured via hybrid means, while there is a larger disparity (57.1g, 63.7g, and 92.1g, respectively) when observing subtractive processing. This disparity is a result of the increased demand for material removal as part complexity increases. For a given bounded part volume, as noted above, with increasing part complexity (SA/V) energy consumption steadily decreases for the hybrid process, while milling energy is seen to increase with complexity. Thus, a level of complexity exists where it is advantageous to switch from milling to hybrid (here, a SA/V of between 0.24-0.39).

3.6 Conclusion

In order to effectively characterize sustainability performance in the rapidly growing space of cyclic manufacturing, the development of a supporting process modeling framework is essential. In particular, there is a deficiency in methodologies used to assess and accurately track sustainability metrics of each subprocess in a cycle that this work aims to remedy. In this research, a manufacturing process modeling framework for evaluating sustainability performance of cyclic manufacturing process was developed. Terminology and mathematical representation were provided for defining and storing product and process information for cyclic manufacturing processes. A UMP quantification and aggregation algorithm was developed and used to store and evaluate sustainability metric information for cyclic manufacturing processes.

Further, the developed process modeling methodology was utilized to characterize a hybrid manufacturing process for evaluating and comparing its environmental performance with a conventional unit manufacturing process (milling) for fabricating products with varying complexities. First, the design and development of the low-cost hybrid manufacturing processes was discussed. Second, the manufacturing process model for the hybrid process was presented. Third, the process model was utilized to evaluate environmental performance for fabricating products with varying complexities using the hybrid process. The results indicated that hybrid manufacturing process has better environmental performance than milling process for the four parts evaluated. Calculated energy consumption was compared to experimental energy consumption and previously reported process energy consumption to validate the manufacturing process model. A low mean absolute error was obtained, establishing the accuracy of the manufacturing process model. Utilizing the framework to develop the manufacturing process model also enabled identification of low performance subprocess in a hybrid manufacturing cycle.

Developers and users of cyclic manufacturing technologies can utilize the manufacturing process modeling framework to characterize, assess, and extract product and process sustainability information of cyclic manufacturing processes through model reusability, extensibility, and composability. The methodology presented herein can enable sustainable decision making during process development, product design, and process planning activities. Future work in support of this research will focus on development of an information modeling approach to facilitate the application of the manufacturing process modeling framework. Another opportunity for future work includes comparing the environmental impacts of remanufactured polymer parts produced using the hybrid process with recycled polymer parts using a non-hybrid process. The model developed in this research for the polymer-based hybrid process includes environmental impacts of manufacturing, and excludes impacts of other life cycle stages, such as raw material extraction, raw material processing, and product end of life. Integrating cyclic manufacturing process models with cradle-to-gate product life cycle assessment will aid sustainable manufacturing decision makers in evaluating the relative performance of new design and manufacturing technologies.

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Chapter 4: A Grey Box Software Framework for Sustainability Assessment of Composed Manufacturing Processes: A Hybrid Manufacturing Case

by
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CHAPTER 4. A GREY BOX SOFTWARE FRAMEWORK FOR SUSTAINABILITY ASSESSMENT OF CYCLIC MANUFACTURING PROCESSES: A HYBRID MANUFACTURING CASE

4.1 Abstract

A lack of consistent data, reliable analysis techniques, and user-friendly tools is inhibiting decision makers' abilities to assess and evaluate the sustainability performance of manufacturing processes and systems. Recent integration of information technology with advanced manufacturing technologies has led to a new paradigm, termed smart manufacturing or Industry 4.0. To leverage this paradigm shift for the advancement of sustainable manufacturing, efforts have been made to characterize unit manufacturing processes (UMPs) for sustainability assessment and to develop frameworks, methodologies, and standards utilizing information modeling approaches. This paper proposes a grey box object-oriented software framework for sustainability assessment of cyclic manufacturing processes, utilizing the multiple inheritance principle for composition of UMP models. Information modeling guidelines based on the framework are provided for UMP model developers and UMP performance analysts to construct and analyze system models. To demonstrate the usefulness of the framework and guidelines, a prototype information model is developed for a hybrid manufacturing system composed of fused deposition modeling (an additive process) and CNC milling (a subtractive process).

4.2 Introduction

In recent years, the synergy of information technologies with advanced manufacturing technologies is changing the way industry designs manufacturing systems. This convergence of humans, technology, and information aims to improve competitiveness and promote strategic innovation in existing manufacturing industry [57]. The application of networked information-based technologies present new manufacturing business opportunities that have not yet been realized [58]. The smart manufacturing paradigm, or Industry 4.0, emphasizes intensified application of manufacturing intelligence throughout manufacturing and supply chain enterprises [59]. The Smart Manufacturing Leadership Coalition (SMLC) accentuated the need for smart manufacturing to support sustainable manufacturing in saying "next-generation software and computing architectures are needed to effectively mine data and use it to solve complex problems [*such as sustainability issues*] and enable decision-making based on a wide range of technical and business parameters" [60].

Today, smart manufacturing with a focus on sustainability has gained traction as companies, individuals, and government organizations strive for superior sustainable manufacturing systems [32]. The National Institute of Standards and Technology (NIST) defines smart manufacturing in a way that also focuses on sustainability [36]: "the synthesis of advanced manufacturing capabilities and digital technologies to collaborate and create highly customizable products faster, cheaper, better, and greener." Environmentally-responsible design and manufacturing has led to a variety of software tools for sustainability assessment [61]. These tools often generate inconsistent results due to a lack of uniform data, models, and methods to represent manufacturing processes and equipment [62]. However, the emerging field of smart and sustainable manufacturing has led research to focus on formal methods, frameworks, and standards to leverage new information technologies for advancing sustainable manufacturing [58].

To address the need for a uniform methodology to represent/ characterize manufacturing processes, the ASTM International E60.13 subcommittee developed and published standard ASTM 3012-16, which provides a methodology for developing unit manufacturing process (UMP) models that manufacturers can use to capture relevant environmental metrics of individual manufacturing processes [16]. UMPs are the smallest elements in manufacturing that add value through transformation of shape, structure, or workpiece properties [24]. UMP characterization in accordance with the standard enables deeper understanding of the process and improves process-level decision making [25]. Researchers are not only constructing information models for various UMPs based on the standard but are also developing methods and frameworks to enable reusability, composability, and extensibility of the models.

The goal of the research presented herein is to realize a software framework that will enable sustainability performance assessment of cyclic manufacturing processes through the composition (or linking) of UMP models. Further, this research provides information modeling guidelines that can assist UMP model developers and UMP performance analysts in constructing and analyzing models of cyclic manufacturing processes. A model of a hybrid manufacturing process composed of fused deposition modeling (an additive process) and CNC milling (a subtractive process) is constructed, as described below, to demonstrate the operational application of this framework.

4.3 Background

The most common software applications for sustainability assessment are based on the life cycle assessment (LCA) methodology [5]. Though LCA tools can inform manufacturers about the environmental impacts of their production processes, they do not facilitate in-depth, process-level analysis [11]. Since they are limited in aiding sustainability evaluation of manufacturing processes, LCA-based applications are not well-suited for early product design [12]. To overcome the deficits of LCA software, product and process information for modeling, including complex sustainability information, should be organized in a structured manner.

Information modeling is common in software engineering for building system architectures and has recently gained popularity in the manufacturing domain [13]. It enables the organization of complex information, such that it can be easily implemented into a software application. Information modeling helps in defining concepts, relationships, rules, and operations to specify data semantics with regard to a domain [12]. Information modeling techniques used in recent manufacturing process modeling practice are based on entity relationships, functional modeling, and object-oriented approaches [6].

Manufacturing process analysis is a recognized need within the sustainable manufacturing research community [14]. As a result, efforts for integrating information modeling approaches with the development of UMP models in accordance with the ASTM 3012-16 standard have been reported. Garretson et al. [15] developed a software application using Visual Basic to assess a set of sustainability metrics for evaluating alternative manufacturing process flows. Madan et al. [16] developed a Visual C# application for predicting energy consumption of a manufacturing process with a focus on tool usability. Shankar Raman et al. [11] developed a methodology to facilitate systematic reuse of UMP models by encapsulating different aspects of complex processes into reusable building blocks. Smullin et al. [17] and Zhang et al. [12] developed methods and applications to compose UMP models. The methodology presented below utilizes a single application framework to provide a approach for constructing individual UMP models, composing two UMP models, and assessing sustainability metrics for evaluating composed UMP models.

The software framework for composing UMP models presented here adopts an object-oriented information modeling approach. Object-oriented modeling enables modularity, reusability, composability, and extensibility of program code by applying four simple and widely accepted principles [18]: (1) encapsulation, (2) abstraction, (3) polymorphism, and (4) inheritance. The framework developed here utilizes multiple inheritance to compose UMP models. The next four sections present the software framework, information modeling guidelines, a demonstration of the approach for a hybrid manufacturing system, and opportunities for future research.

4.4 Software Framework

As noted above, the software framework developed for composing UMP models adopts an object-oriented information modeling approach utilizing the multiple inheritance principle (Fig. 4.1). Object-oriented modeling allows us to organize program code as a collection of objects that consist of both data and behaviors [19]. Object-oriented programming is based on the following characteristics [20]:

- Developers define new classes of objects
- Objects have defined operations
- Instantiation creates an instance of the class to be operated
- Classes share common components using inheritance

The inheritance principle enables reuse of code for existing classes or for establishing a new subclass from existing classes [63]. Parent classes allow us to create child classes through multiple inheritance; if class C inherits from class A and class B, we can consider class C as the child class of parent classes A and B. As such, parent classes create a pattern on which child classes can be based, and child classes make use of the attributes and methods of the parent classes [63]. Translating the inheritance principle to UMP modeling, we consider parent classes as individual UMP models that are to be composed to form a new model. A child class would be the composed UMP model that inherits product information, process information, and transformation functions from the parent UMP models.

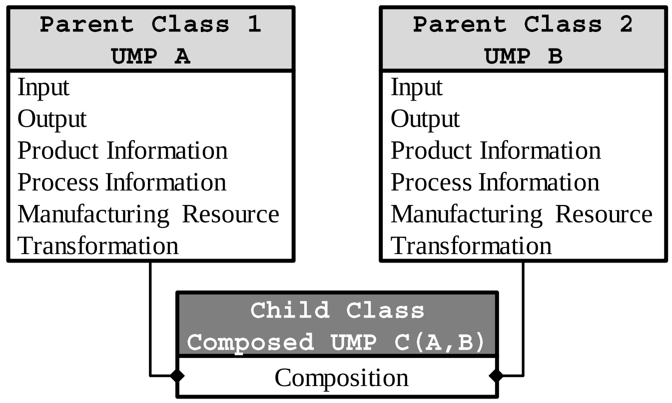

Figure 4.1: Multiple inheritance principle for UMP model composability

Inheritance facilitates more rapid development of software frameworks through reusability, composability, and extensibility. A software framework is a set of modules that work together where common code with generic functionality can be selectively customized by application developers [64]. An object-oriented software framework is "a reusable design of an application or subsystem, represented by a set of abstract classes and the way objects in these classes collaborate" [65]. Object-oriented frameworks fall into three main categories according to their level of extensibility: (1) white box, (2) black box, and (3) grey box frameworks, as described below.

A *white box framework* is an architecture-driven framework, where the architecture of the framework must be known to application developers. Flexibility and customization of the framework is provided by the inheritance mechanism [64]. Instantiation in white box frameworks requires programming and creation of classes, which can be introduced by inheritance or composition. The framework is easy to design but difficult to learn. A *black box framework*, on the other hand, is a data-driven framework. Classes and codes are created by automated instantiation, hiding the complex details from the user. The internal structure of the framework's architecture is also hidden and the user needs to know only the hotspots of the framework's architecture and its general description [66].

Customization is only made through composition, and flexibility is limited. These frameworks allow the instantiating user to have less knowledge of the architecture. This framework is difficult to design but easy to learn. A *grey box framework* contains both white box and black box characteristics to realise the benefits of both [66], and has been adopted for this research, as shown in Fig. 4.2.

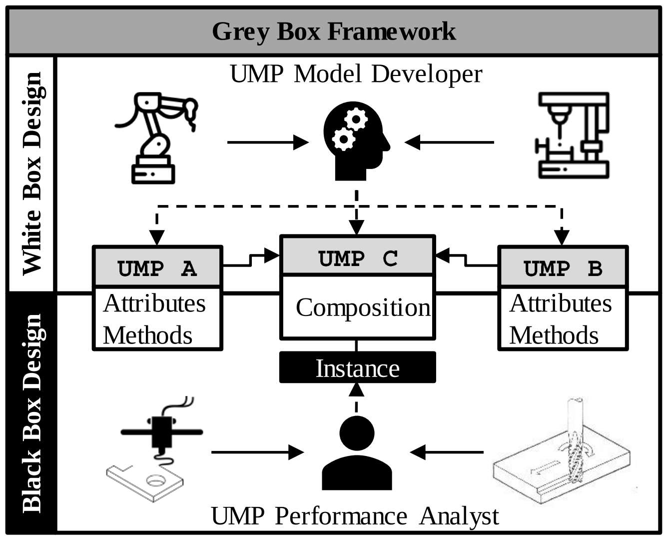

Figure 4.2: A grey-box-object-oriented framework for UMP model development (White box) and UMP performance analysis (Black box)

UMP model developers can be researchers and industrialists motivated in characterizing UMPs in accordance to the ASTM 3012-16 standard to capture relevant sustainability metrics of interest. Developers could construct UMP models for individual manufacturing processes, as well as composing UMP models to capture relevant environmental information of manufacturing process flows, for example. UMP model developers utilize the white box design elements of the grey box software framework. Developers must have knowledge of the white box architecture to develop and compose UMP models. In Fig. 5.2, UMP A and UMP B represent parent classes, and UMP C represents a child class inherited from the parent classes. While developing the parent classes, the developer must define the attributes and methods that describe the classes. *Attributes* can be considered as product and process information, and *methods* can be considered as transformation functions. Developers need to have in-depth knowledge of the manufacturing processes to be able to construct and compose UMP models with ease.

UMP performance analysts are end users motivated in evaluating various manufacturing processes or manufacturing process flows to evaluate the impacts of their product designs. Since performance analysts only need to know the hotspots of the architecture and not its internal structure, analysis tools would utilize the black box design elements of the grey box software framework. In the developed framework, an *instance* is the hotspot where the end user can enter product information for evaluating the composed (child) manufacturing process.

4.5 Information Modeling Guidelines

The architecture of the developed software framework was discussed in the previous section. This section provides guidelines (Fig. 4.3) based on the framework to assist UMP model developers and UMP performance analysts in constructing and analyzing UMP models. For demonstration of the framework, a software application was built using Python 3.0 as the programming language, as described in Section 5.

UMP model developers can construct and compose information models of various manufacturing processes using the following white box design guidelines:

- Create a class called "UMP 'A,'" where A is the respective manufacturing process name, to construct an information model for that manufacturing process.
- Create a constructor, or "`__init__`," method to define product information and control parameters. Product information includes information required for evaluation of the relevant manufacturing process, such as part volume, part geometry, and part height. Control parameters include tunable parameters that can be adjusted to evaluate different process settings, such as depth of cut and spindle speed in a computer numerical controlled (CNC) milling operation [16].
- The constructor method will be called each time an instantiation takes place, so that the developed model can be used to evaluate each cycle.
- Create a method for defining process information, which includes fixed parameters, intermediate variables, and metrics of interest. *Fixed parameters* are parameters set through the evaluation of transformation equations, e.g., spindle motor power in a milling machine [16]. *Intermediate variables* include calculated variables required to

complete evaluation of the transformation equations, e.g., machining time is calculated to determine machining energy use. *Metrics of interest* include UMP performance metrics, e.g., energy consumed or cost per part.

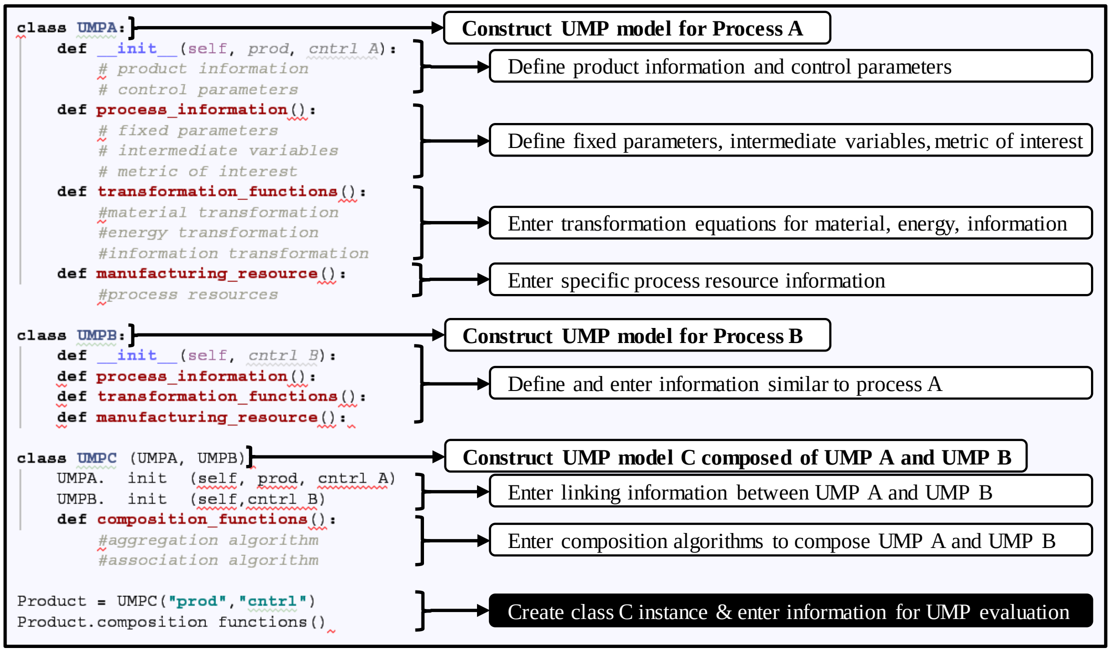

Figure 4.3: Framework information modeling guideline for UMP model developers and UMP performance analysts

- Create a method to include transformation functions that describe process inputs and outputs and metrics of interest using product and process information.
- Create a method to capture resource information for the manufacturing process, e.g., tooling and labor requirements.
- Create a class called "UMP 'B'" for another manufacturing process (process B) as described for process A.
- Create a child class "UMP 'C'" for composing parent classes UMP "A" and UMP "B" for composed process C.
- Enter linking information for UMP A and UMP B needed to compose the UMPs, forming UMP C. Linking information again includes product information and control parameters.

- Create a composition function under class UMP "C" and include aggregation and association algorithms to compose UMP "A" and UMP "B" using the linking information.

UMP performance analysts can evaluate manufacturing processes for their products using black box design guidelines:

- Create an instance of the child class UMP "C" and enter product information and control parameters for the specific product design alternatives and process setting scenarios.
- Assign the composition function to the created instance for performance evaluation of composed UMP "C."

4.6 Composing UMPs for Hybrid Manufacturing

The software framework developed above is applied to construct an information model for an in-house, low-cost hybrid manufacturing system capable of both additive and subtractive manufacturing processes. A hybrid manufacturing system can be defined as a combination of processes on a single machine [67]. Hybrid manufacturing systems comprised of integrated UMPs aim to reduce time-to-market, shorten the manufacturing process chain, and cut production cost. The design of this hybrid manufacturing system involves retrofitting a CNC mill with 3D printer components. A schematic representation of the hybrid manufacturing system is shown in Fig. 4.4.

The predominant manufacturing process of this system is fused filament fabrication, which enables the process to achieve a near netshape part. Using an extruder attached to the head of the CNC mill to take advantage of its Z-direction motion, material is melted and deposited layer-by-layer onto a textured build platform. CNC motion generating software is used to drive the build platform for both printing and milling. Stepper motors (NEMA 34) in conjunction with a ball screw system drive the build platform. A microcontroller board (RAMBo v1.3) controls 3D printing functions, including heating and cooling processes along with extrusion rates. Post-processing of the 3D print is done through a CNC milling operation using an endmill.

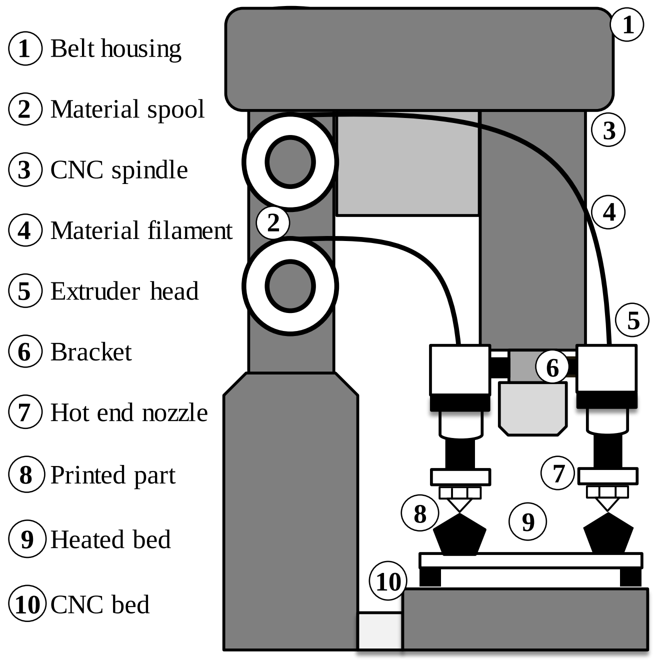

Figure 4.4. Developed dual extrusion hybrid manufacturing system

This hybrid manufacturing system was characterized by implementing models into a software application in accordance with the ASTM standard described above. While the complexity of the parent processes required numerous lines of code, only partial code under each subsection (method) of the entire application is reported here due to space restrictions. Figs. 4.5a-4.5c display code for additive manufacturing, Figs. 4.5d-4.5f display code for subtractive manufacturing, and Figs. 4.5g-4.5h display code for the composed hybrid manufacturing system.

Figs. 4.5a and 4.5d display code for creating a class and constructor method for additive and subtractive processes, respectively. The constructor method with the *self*-keyword is used to make product information and control parameters accessible for evaluation. Figs. 4.5b and 4.5e display code for creating a process information method for both parent UMPs. Fixed parameters in this method are given values relevant to machine specifications. Figs. 4.5c and 4.5f display code to describe transformation functions for both UMPs. Fig. 4.5g displays code for composing both processes using the aggregation algorithm. Fig. 4.5h displays code for instantiating the child class to evaluate hybrid UMP metrics for a particular product; the code represents the *hotspot* for UMP performance analysts to provide product and process-specific information.

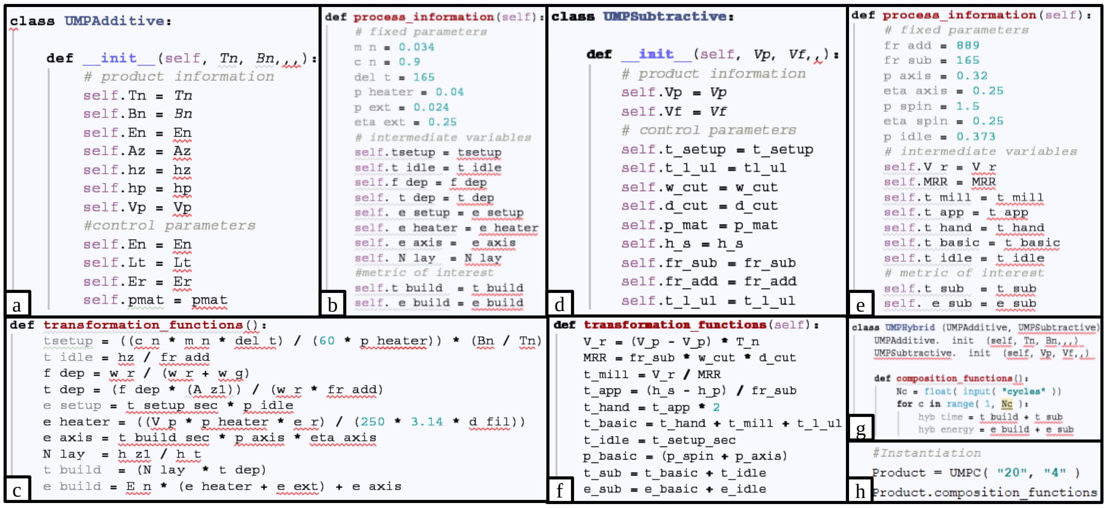

Figure 4.5: Demonstration for hybrid manufacturing (Model code for a-c: Additive process; d-f: Subtractive process; g: Hybrid process; and h: Product evaluation)

4.7 Summary

The developed software framework enables UMP model developers and analysts to create and compose information models for performing sustainability characterization of manufacturing processes and systems. Information modeling guidelines were presented to help realize the framework, and provide step-by-step instructions for model developers to construct and compose information models using white box design methods. Further, the guidelines provide instructions to UMP performance analysts for utilizing black box design principles to analyze composed models for evaluating product design alternatives. In addition, an application of the framework was presented for a hybrid manufacturing system composed of additive (FFF) and subtractive (CNC milling) processes.

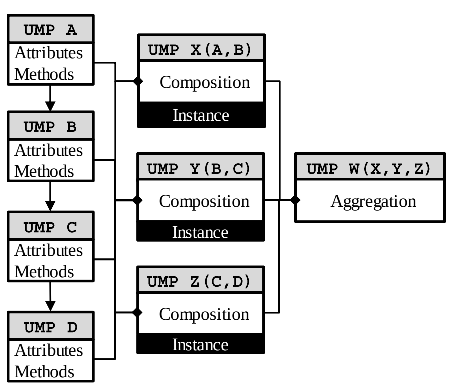

Figure 4.6. Adopting multi-level and multiple inheritance principle for assessing manufacturing process flows

To demonstrate the application of the approach from a user perspective, a graphical user interface will be developed and demonstrated as future work. The software framework adopting multiple and multi-level inheritance shown in Fig. 4.6 will be applied to compose multiple UMP models to illustrate improved accuracy of sustainability characterization for manufacturing process flows. As shown in the figure, multi-level inheritance can be used to derive a new child (grandchild) class from existing child classes. Thus, UMP W can be derived as a grandchild of UMPs A, B, C, and D by aggregating the performance metrics of their child classes UMPs X, Y, and Z. In this way, complex systems of integrated processes in series, in parallel, and in hybrid configurations, can be readily modeled. Further, the resulting models will be extensible, reusable, and composable, enabling rapid sharing of existing process information models within and across industry domains.

Chapter 5: Effectiveness of a Standards-Based Cyclic Model for Characterizing Energy Consumption in a Hybrid Manufacturing Process

by
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CHAPTER 5. EFFECTIVENESS OF A STANDARDS-BASED CYCLIC MODEL FOR CHARACTERIZING ENERGY CONSUMPTION IN A HYBRID MANUFACTURING PROCESS

5.1 Abstract

ASTM International has recently published standards to provide uniform methodology for representing manufacturing processes, enabling the consistent evaluation of changes in environmental impacts due to modifications in individual manufacturing processes. While the sustainable manufacturing community has applied these standards in modeling individual manufacturing processes, there exists limited research in characterizing environmental impacts of hybrid manufacturing process which have a complex, integrated, and cyclic nature of subprocesses. In addition, there is a dearth of methods to evaluate the effectiveness of models developed based on the standard. The work herein addresses this deficit by evaluating the effectiveness of a standards-based cyclic model for characterizing hybrid manufacturing process energy consumption. To support this research, a dual extrusion hybrid additive subtractive manufacturing (DE-HASM) process is developed and the modeling approach is applied to characterize energy consumption of the DE-HASM process. The approach undertaken to evaluate model effectiveness is provided based on three baselines. The analysis indicates that the cyclic model is effective for all three baselines.

5.2 Introduction

With sustainability being an influential factor in new product design and manufacturing [68], various modeling techniques have been developed and implemented over the past decade to characterize and assess the social, economic, and environmental performance of manufacturing processes [34]. A major subset of modeling techniques for characterizing and assessing sustainability performance of manufacturing processes includes life cycle assessment (LCA) tools, which guide manufacturers in making informed decisions about the environmental impacts of their production processes and supply-chain activities [69]. However, LCA methodology lacks a flexible representation of manufacturing processes, constraining their ability to consistently evaluate changes in environmental impacts due to modifications in individual manufacturing processes [25]. To overcome this constraint in characterizing manufacturing processes for sustainability-related decisions, ASTM International has recently published standards ASTM E2986-15 [5] and ASTM E3012-16 [6].

While researchers have applied these standards in modeling sustainability performance of individual manufacturing processes, novel manufacturing approaches are leading to the integration of multiple subprocesses into a single process or machine. In particular, hybrid manufacturing processes are gaining traction due to their suitability for the production of parts exhibiting complex geometries and utilizing advanced materials [1]. Hybrid manufacturing processes exhibit a cyclic nature and enable flexible and rapid production, effectively shortening the time-to-market, decreasing the manufacturing process chain, and reducing production costs [8]. Sustainability characterization of hybrid manufacturing is a challenge due to the complex, integrated, and cyclic nature of subprocesses, which require a higher level of information synthesis than individual processes [9]. With the growing development and adoption of hybrid processes, however, it is necessary for developers and users of these technologies to incorporate broader sustainability considerations during process development, product design, and process planning activities.

The research herein evaluates and compares the effectiveness of a standards based cyclic model for characterizing hybrid manufacturing process energy consumption. In conducting this research, the following questions arose: 1) *How can the ASTM E3012-16 standard be applied to facilitate environmental impact characterization of hybrid manufacturing processes?* and 2) *How can the effectiveness of the developed cyclic model be evaluated?*

The remainder of the paper is organized into five sections. Section 2 discusses research efforts supporting hybrid manufacturing process development and introduces a dual extrusion hybrid additive subtractive manufacturing (DE-HASM) process developed to support this research. Section 3 describes the developed standards-based cyclic model for characterizing DE-HASM process energy consumption. In Section 4, the approach undertaken to evaluate the effectiveness of the model is introduced and the analysis results are presented and discussed. Finally, Section 6 reports the implications of this research and presents opportunities for future research.

5.3 Hybrid Manufacturing Process Development

5.3.1 Related Process Research and Development

Hybrid manufacturing processes are increasingly being recognized as a means to meet production goals, such as reducing equipment and space needs, and shortening processing, inspection, and handling times [12]. The key advantage of hybrid manufacturing is the ability to overcome the limitations of individual processes that cannot be otherwise eliminated due to process technology constraints. Hybrid manufacturing processes open up new opportunities and applications for fabricating components that cannot be produced efficiently by using currently available process technologies [13]. To provide a deeper understanding of hybrid processes, a collaborative working group of the International Academy for Production Engineering (CIRP) dealing with hybrid processes provided descriptive definitions [42]:

- Open definition: *A hybrid manufacturing process combines two or more established manufacturing processes into a new combined set-up whereby the advantages of each discrete process can be exploited synergistically.*
- Narrow definition: *Hybrid processes comprise a simultaneous acting of different (chemical, physical, controlled) processing principles on the processing zone.*

In the context of the research presented herein, a hybrid process is a synergistic combination of an additive and a subtractive process exhibiting a cyclic nature in a single machine for improving part quality, part functionality, and manufacturing productivity [14]. This approach has been termed *hybrid additive subtractive manufacturing* (HASM), and can involve sequential (additive to subtractive) or iterative (a series of additive and subtractive) process steps. Hybrid processes require novel approaches to fixturing and orientation to fabricate a part, as well as process integration and process planning aspects, which have been explored in prior research as highlighted below.

Process integration studies relevant to HASM processes provide knowledge on mechanical, electrical, and software integration for various combinations of additive and subtractive processes. For example, details on the mechanical and software integration for a 5-axis hybrid manufacturing system combining a laser deposition additive process with CNC milling, known as LAMP, was provided by Nagel et al. [8]. The LAMP system aimed to increase build-size capability, and improve the accuracy and surface finish of metal structures with minimal post-processing. Similarly, Karunakaran et al. [43] described the mechanical, electrical, and software integration for retrofitting arc welding unit components on a CNC mill at a low cost. This system was developed to achieve both near net shape metal deposition and finish machining on the same machine. While these two studies focused on metal parts, Lee et al. [12] provided an approach to integrate FFF and 5-axis CNC milling to produce polymer parts without support structures. They also demonstrated the printing of polymer around embedded metal supports to increase overall part strength.

Prior research has also investigated the efficient use of hybrid processes in production by considering their influence on microplanning and macroplanning activities, including automated process planning and tool path generation for HASM processes. Merklein et al. [70] presented a procedure and software prototype through which NC tool paths for laser cladding of complex parts on a 5-axis CNC mill can be directly generated from a CAD model. Ren et al. [44] developed an integrated process planning framework with an aim to automate the hybrid manufacturing process. Using their process planning software, they demonstrated automated fabrication of functional parts by combining laser deposition and machining within a single setup. Nau et al. [45] provided an approach for hybrid process development and also demonstrated a general approach for risk and potential analysis of hybrid manufacturing technologies to aid process integration decision making. In support of production studies, mechanical and material characterization has provided knowledge about the performance of components manufactured using HASM processes. One of such studies include that of Du et al. [47] which compared the microstructure and hardness variations in an 18Ni maraging steel part fabricated using a HASM process and a conventional AM process. They found that the parts fabricated using the HASM process exhibited a higher density and hardness.

To achieve the objective of this research, which herein is to evaluate the effectiveness of a developed standards-based cyclic model for characterizing and assessing hybrid process energy consumption, a hybrid manufacturing process integrating fused filament fabrication and CNC milling was developed at Oregon State University, and this work is explained in the next section.

5.3.2 DE-HASM Process Development

The design and development of a low-cost hybrid process, shown schematically in Fig. 5.1. The process, called dual extrusion hybrid additive subtractive manufacturing (DE-HASM), combines fused filament fabrication (a polymer-based additive process) and CNC milling (a subtractive process). These integrated processes have the ability to produce and post-process parts directly from the CAD representation, achieving good surface finish in a single setup. The DE-HASM process involves integration of two low-cost 3D printing extruder heads with a benchtop CNC mill. The uniqueness of the process is that it enables ditto printing by extruding duplicate parts simultaneously, resulting in nearly twice the productivity.

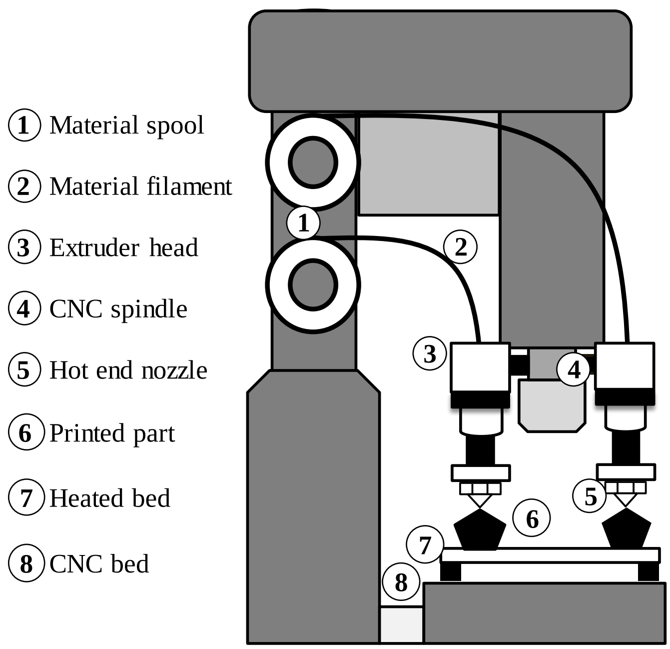

Figure 5.1: Schematic representation of the DE-HASM process

Figure 5.2 provides a functional representation of the DE-HASM process. The automated toolpaths for both processes (extrusion and milling) are generated using an open-source slicing software (Slic3r). The resulting lateral and vertical movements for both processes are accomplished using the table and spindle driver motors of the CNC milling machine. Material is extruded layer-by-layer through two FFF extruder heads onto a heated bed, which is fastened to the X-Y motion-controlled table of the mill. The extruder heads are attached to the quill of the mill to take advantage of its Z-direction motion controller. The low-cost 3D printer controller (RAMBo v1.3 control board) selected is capable of executing extrusion and motion control commands based on the desired build paths and temperature feedback. In this setup, only the extrusion and heated nozzle functions are used (both are on/off control). Post-processing of the part is done through a semi-automated CNC milling operation using an endmill. In the current proof-of-concept, the ability to perform hybrid toolpath generation is limited and requires an expensive commercial software license.

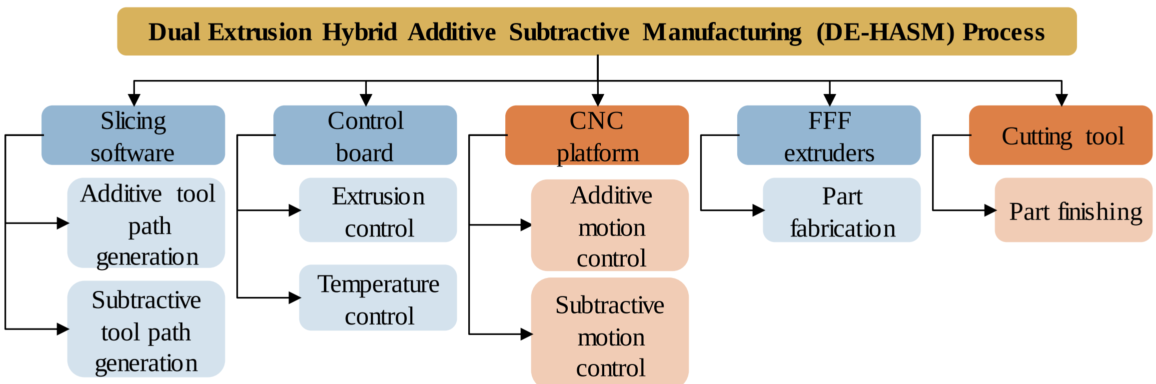

Figure 5.2: Functional representation of the DE-HASM process

The DE-HASM process route enables the reduction of process steps relative to conventional additive-subtractive fabrication of polymer parts, as shown in Fig. 5.3. The conventional route involves six process steps, whereas the DE-HASM route requires only four process steps. First, in the developed DE-HASM proof-of-concept, printing toolpaths are generated using the slicing software. The surface toolpaths are repurposed for controlling the CNC mill during cutting. When toolpath generation cannot be automated, for example when an extrusion raster pattern is generated that would result in the removal of subsequently printed feature, a manual milling process is used. To maintain positional accuracy, the printed part in the hybrid route would require only the installation of clamps to the bed prior to machining, resulting in elimination of the setup step for machining process. For the parts produced in this research, clamping was not necessary given the low cutting forces.

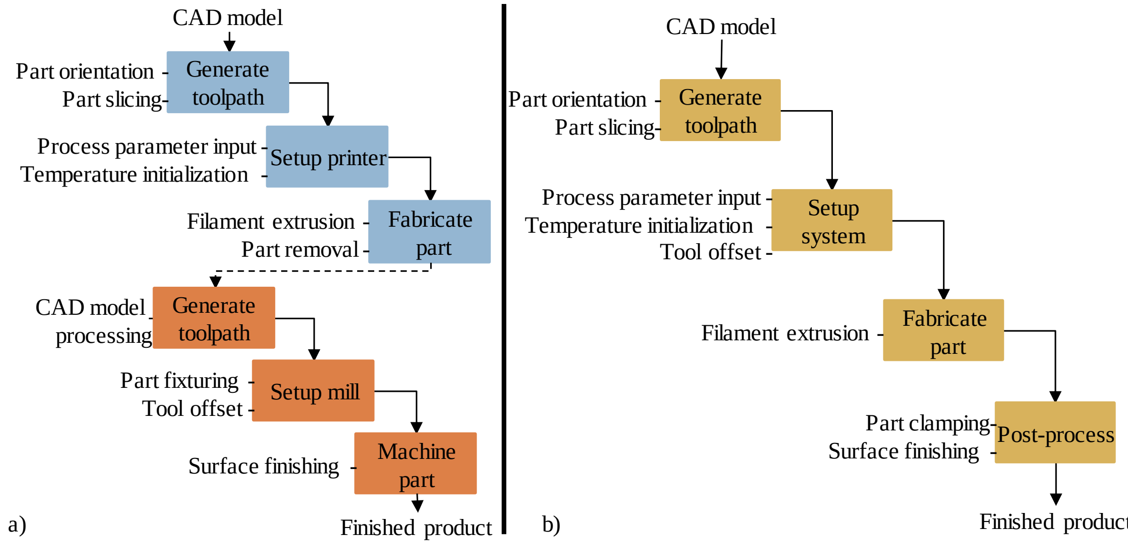

Figure 5.3: Process route for fabricating a polymer part in a) conventional additive-subtractive route and b) DE-HASM route

5.4 Manufacturing Process Modeling

5.4.1 Approaches for Manufacturing Process Modeling

While prior work has been done to understand the performance of integrated processes and process planning for hybrid processes, no studies have been reported that investigate the energy, materials, or cost impacts of using HASM processes in production environments. However, a large body of knowledge exists within research reported by the sustainable manufacturing community over the past three decades for individual manufacturing processes (UMPs) that comprise hybrid processes. These studies have largely focused on process energy and materials efficiency, but also have led to standard sustainability assessment methods for manufacturing processes and systems, which can be applied to HASM processes. This prior work is briefly discussed in the next two subsections.

5.4.1.1 Process level modeling

Researchers in the sustainable manufacturing community have developed and applied mechanistic models to characterize and assess energy consumption in additive and subtractive manufacturing process. For example, Baumers et al. [18] developed a combined model to estimate build time, energy consumption, and cost in material jetting process. Energy consumption could be estimated using the developed model with a mean average error of 15.31%. The proposed model to estimate build time accounts for the motion of the print head during material deposition. The build time model is compared for two deposition scenarios, one in which deposition time per layer is fixed and a second relating total build to deposition area per layer. The authors concluded that both scenarios produce significant estimation errors. Similarly, energy and material flow analysis in a binder-jetting process was performed by Meteyer et al. [17]. Their main aim was to estimate energy consumption in a metal binder jet process. The unit process modeling approach was undertaken to provide life cycle inventory (LCI) data for life cycle analysis (LCA) of the processes. Experimentation and data analysis was performed to determine correlations between process parameters and LCI data. The model was used to estimate printing process energy with 98% accuracy. The authors concluded that energy data could aid in creating LCI for further LCA studies.

Similar efforts have been undertaken to characterize energy consumption in subtractive processes, which can be used to support analysis of HASM processes. Diaz et al. [21] characterized specific energy consumption of a three-axis milling machine to study the effect of material removal rate on energy consumption. The authors reviewed strategies for characterizing and reducing energy consumption of milling machine tools during their use. The approach enables characterizing energy consumption as a function of process rate. The study showed that machining time dominates energy consumption. They extended the work by comparing the differences in machine power demand for cutting aluminum and polycarbonate workpieces. Further, to provide a reliable estimation of energy consumption in a milling process under various machining conditions, Li et al. [23] developed mathematical models based on thermal equilibrium and empirical modeling. The presented energy consumption model was a function of material removal rate and spindle speed. The developed model provided high level accuracy for estimating energy consumption. The models were validated on a number of milling processes under various material removal rates. Efforts to extend the validation of model with other factors is necessary, as noted in the future research.

5.4.1.2 System level modeling

As mentioned earlier, to address the need for uniform methods and software tools for characterizing manufacturing processes and systems, the ASTM International E60.13 subcommittee developed and published standard ASTM 3012-16 [16]. The standard provides a methodology for developing UMP models that manufacturing researchers and practitioners can use to quantify, assess, and improve the sustainability performance of manufacturing systems from the perspective of materials and energy use. As noted above, UMPs are the smallest elements in manufacturing that add value through transformation of shape, structure, or workpiece properties [24]. UMP characterization in accordance with the ASTM standard enables deeper understanding of the process and can improve process-level decision making [25]. Further, composing UMP models can enhance manufacturing system-level understanding and improvement.

While researchers have recently applied the ASTM 3012-16 standard to characterize environmental impacts of various individual manufacturing processes, the Unit Process Life Cycle Inventory (UPLCI) methodology [26,27] was one of the initial efforts reported for developing methods for unit manufacturing process characterization. The aim of the UPLCI approach was to enable formalization of a framework for inventory analysis of the manufacturing stage of the product life cycle. It was noted that dividing a manufacturing process into sub process models enabled reliability and precision. The approach facilitated sustainability analysis of manufacturing systems by aggregating life cycle inventory data of unit manufacturing processes that comprised the manufacturing system.

In parallel with this initial work, a sustainability characterization methodology for UMPs was reported by Madan et al. [28], as a precursor to the ASTM standard. The developed methodology was applied to characterize energy consumption in injection molding, which involved selection and determination of process parameters, defining mold cavity details, selection of the injection molding machine, theoretical calculations for cycle time, and estimation of energy consumption. A structured information model, as currently contained in the ASTM standard, was not developed as part of their work, which restricted information flow across the design and manufacturing domains for the injection molding process application. Doran et al. [29] developed an approach to compare the sustainability performance of additive and subtractive manufacturing processes based on UMP modeling.

Their main aim was to compare the economic, environmental, and social impacts of producing a functional part using direct energy deposition (additive process) with milling (subtractive process). Populating UMP metrics into a life cycle assessment framework enabled the evaluation of sustainability impacts of both processes to determine which manufacturing method might be more appropriate during process planning based on selling price (economic), greenhouse gas emissions (environmental), and injuries/part (social). Their conclusions were limited by the material and process types investigated, and the resulting relationships (e.g., greenhouse gas emission in relation to final part volume) were not validated against actual process data.

5.4.2 A Cyclic Model for Hybrid Manufacturing Process Energy

This section describes the developed standards-based cyclic model for characterizing DE-HASM process energy consumption and answers the first research question: *How can the ASTM E3012-16 standard be applied to facilitate environmental impact characterization of hybrid manufacturing processes?* The standards-based model (Fig. 5.5) is a mechanistic model developed based on manufacturing process modeling framework for cyclic manufacturing processes [71]. A mechanistic model is one which describes the physics of a complex system by examining the workings and establishing the relationship of its individual parts [10]. A mechanistic model should be constructed using the maximum possible features of the system as observations or data will allow. The transformation equations in Figure 5.5 represents the mechanistic model and is described in detail below.

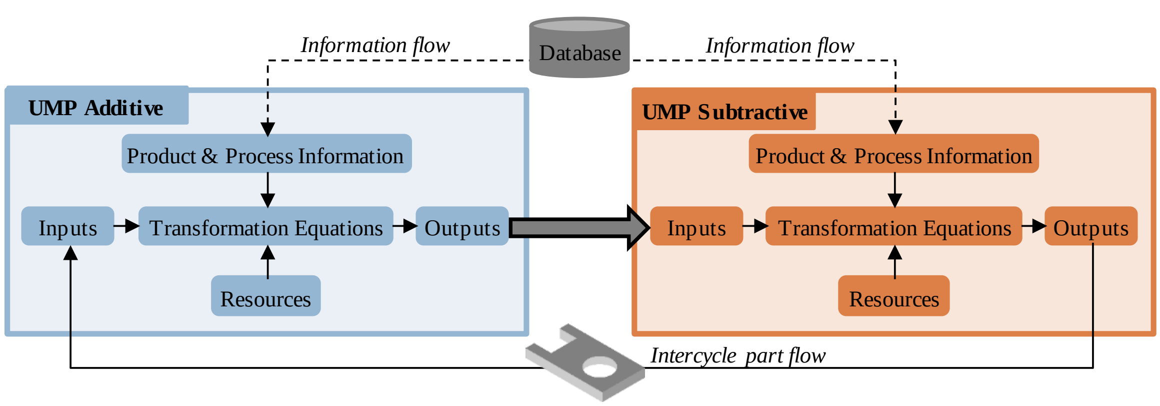

Figure 5.5: Conceptual cyclic model representation to characterize hybrid process energy

The mechanistic model was developed based on first principles for evaluating energy consumption in the DE-HASM process. For the two sub-processes, the model considers geometric factors and process factors that affect energy use. Part features that are additively manufactured are termed additive zones and denoted by *az* and features that are fabricated through material removal are termed subtractive zones and denoted by *sz*. Each zone has a specific length, width, and height. To evaluate the energy consumed by the DE-HASM process, process time is first calculated. Process time involves the summation of additive process time (i.e., heating time and build time) and subtractive process time. Heating time is dependent on the time required to melt the material and can be calculated using Eq. 5.1:

$$t_{heating} = \left(\frac{c_n * m_n * \Delta T_n}{p_n}\right) * \left(\frac{T_n}{B_n}\right) \tag{5.1}$$

where c_n is the specific heat capacity of the material, m_n is the mass of the material extruded in one build, ΔT_n is temperature difference between the initial (e.g., room temperature) and melting temperature of the material, and p_n is the power consumed by the extruder heater block. The result of the first part of this expression, which determines the time to melt the material for one build, is multiplied by the number of builds to meet production demand. The number of builds is determined by dividing the production volume (T_n) by the number of parts per build (B_n). Next, build time is calculated; it is comprised of repositioning time (the time taken to reposition the extruder head from one layer to the next layer in the z-direction) and deposition time (the time to deposit a layer of material). Repositioning time can be calculated using Eq. 5.2:

$$t_{rep\_az\_i} = \frac{h_{az\_i}}{f_{r\_add\_z}} \tag{5.2}$$

where h_{z_i} is the height of zone *i* and $f_{r\_add\_z}$ is the retraction feed rate of the quill in z-direction, used for the additive process. Each zone is defined by a constant cross-sectional area from the part base to the top surface. Repositioning time is calculated for each zone individually. Deposition time can be calculating using Eq. 5.3:

$$t_{dep\_az\_i} = f_{dep} * \frac{A_{az\_i}}{w_r * f_{r\_add}} \tag{5.3}$$

where A_{az_i} is the cross-sectional area of zone *i* and w_r is the road width. Similar to repositioning time, deposition time is calculated for each zone separately. In Eq. 3, f_{dep}, is the deposition fraction and can be considered as the infill density; it is calculated using Eq. 5.4, where w_g is gap between adjacent roads.

$$f_{dep} = \frac{w_r}{w_r + w_g} \tag{5.4}$$

The layering time for each zone is the summation of the deposition time and repositioning time for each layer, as given by Eq. 5.5.

$$t_{lay\_\mathrm{az}\_i} = t_{dep\_\mathrm{az}\_i} + t_{rep\_\mathrm{az}\_i} \tag{5.5}$$

The number of layers per zone is calculated using Eq. 5.6:

$$N_{lay\_\mathrm{az}\_i} = \frac{h_{az\_i}}{l_t} \tag{5.6}$$

where h_{az_i} is the height of zone *i* and l_t is the layer thickness. Build time for a single part is determined by calculating the product of layering times for each zone with their respective numbers of layers and then summing the layering times for all zones (Eq. 5.7).

$$t_{build} = \sum_1^i (t_{lay\_\mathrm{az}\_i} * N_{lay\_\mathrm{az}\_i}) \tag{5.7}$$

The additive process time for the entire production volume is calculated using Eq. 5.8:

$$T_{add} = \left(\frac{t_{build} * T_n}{E_n}\right) + t_{heating} \tag{5.8}$$

where E_n is the number of extruders performing ditto printing and t_{setup} is the time required to create the build plan and prepare the machine for fabrication. Next, subtractive process time is calculated by determining the material removal rate, which is given by Eq. 5.9, adopted from Groover [72]:

$$MRR = f_{r\_sub} * w * d \tag{5.9}$$

where f_{r_sub} is the feed rate for the subtractive process, w is the width of cut, and d is the axial depth of cut. Cutting time for zone *i* is determined by dividing volume of material removed in zone *i* (v_{sz_i}) by the material removal rate. Cutting time for all the zones is then calculated as the summation of milling times for each zone (Eq. 5.10).

$$t_{cut\_z} = \sum_1^i \frac{V_{sz\_i}}{MRR} \tag{5.10}$$

The remaining components of subtractive process time include non-cutting time, comprised of approach/overtravel time and retraction time, and loading/unloading time, which can be calculated using Eqs 5.11-5.14 (refer to the detailed explanation by Kellens et al. [73]). The total subtractive process time is determined for the entire production volume using Eq. 5.11.

$$t_{app} = \frac{(H_p - A_p)}{f_{r\_sub}} \tag{5.11}$$

$$t_{ret} = \frac{(A_p - H_p)}{f_{r\_sub}} \tag{5.12}$$

$$t_{non-cut} = t_{app} + t_{ret} \tag{5.13}$$

$$t_{mill} = t_{hand} + t_{cut\_sz} + t_{l/_{ul}} \tag{5.14}$$

$$T_{sub} = \left(t_{hand} + t_{mill} + t_{l/_{ul}}\right) * T_n \tag{5.15}$$

Hybrid process time is determined by summing the additive process time and subtractive process time (Eq. 16).

$$T_{hyb} = T_{add} + T_{sub} \tag{5.16}$$

With the process times determined, process energy now can be calculated. Additive process energy includes setup energy and build energy. Setup energy is given by Eq. 5.17:

$$e_{setup} = t_{setup} * p_{idle} \tag{5.17}$$

where p_{idle} is the power consumed by the CNC mill during the machine setup process. Build energy is comprised of the heater block energy, energy consumed by the axis, and extruder motor energy. The heater block energy is the energy required to heat the filament to its melting point (Eq.5.18):

$$e_{heater} = \frac{V_p * p_{heater} * e_r}{\pi * r^2} \tag{5.18}$$

where V_p is the volume of printed material, p_{heater} is the power rating of the heater block, e_r is the extrusion rate, and r is the radius of the filament. Energy consumed by CNC axis motor for x, y, and z motion is given by Eq. 5.19:

$$e_{axis} = t_{build} * p_{axis} * \eta_{axis} \tag{5.19}$$

Energy consumed by extruder motor to feed the filament for extrusion is given by Eq. 5.20:

$$e_{ext} = t_{build} * p_{ext} * \eta_{ext} \tag{5.20}$$

where p_{axis} and p_{ext} are the power of axis motor and extruder motor respectively, and η_{axis} and $\eta_{extruder}$ are the efficiencies of the axis motor and extruder motor, respectively. The energy needed for a single build and the total energy required for the additive process are given by Eqs. 5.21 and 5.22.

$$e_{build} = e_{ext} + e_{heater} + e_{axis} \tag{5.21}$$

$$E_{add} = (T_n * e_{build}) + e_{setup} \tag{5.22}$$

Components of subtractive process energy include axis energy, spindle energy, and idle energy. The total milling process energy is determined for the entire production volume and these are represented by Eqs. 5.23-5.26, as adopted from Kellens et al. [73],

$$e_{axis} = t_{mill} * p_{axis} * \eta_{axis} \tag{5.23}$$

$$e_{spin} = t_{cut\_z} * p_{spin} * \eta_{spin} \tag{5.24}$$

$$e_{idle} = t_{idle} * p_{idle} \tag{5.25}$$

$$E_{sub} = T_n * (e_{axis} + e_{spin} + e_{idle}) \tag{5.26}$$

Hybrid process energy is determined by summing additive process energy and subtractive process energy, given by Eq. 27:

$$E_{hyb} = E_{add} + E_{sub} \tag{5.27}$$

The cyclic model provides the relationship between design parameters (e.g., part volume, part height, and surface area), process parameters (e.g., extrusion rate and feed rate) and metrics of interest (e.g., hybrid process time and hybrid process energy) in a polymer-based hybrid process, but also can be applied to other HASM processes, more generally.

5.5 Model Effectiveness

5.5.1 Evaluating Model Effectiveness

As mentioned earlier, researchers have undertaken efforts to characterize the sustainability performance of unit manufacturing processes (UMPs), but there is a dearth of methods to evaluate the effectiveness of such models. In an effort to evaluate the effectiveness of the standards-based cyclic model developed in this research, research questions are drafted based on three baselines, as described below.

- The first baseline is the *ability to evaluate process plans of cyclic processes and identify low performing cycles and cycle operations*. This baseline is tested by answering the following question: Can the cyclic model evaluate energy consumption of alternative process plans for a particular product?
- The second baseline is *model accuracy*. This baseline is tested by answering the following research question: What is the variation (percentage error) of model-predicted to experimentally-measured hybrid manufacturing process energy consumption?
- The third baseline is the *ability to identify a correlation between process energy consumption and part complexity*. This baseline is tested by answering the following

research question: What is the correlation between model-predicted process energy consumption (additive, subtractive, and hybrid) and part complexity?

- The fourth baseline is the *ability to identify a correlation between subprocess energy consumption and part complexity*. This baseline is tested by answering the following research question: What is the correlation between model-predicted hybrid subprocess energy consumption and part complexity?

To test Baseline 1, a test article was developed based on a part reported by Groover [72] to have a poor design, since it would require multiple machining setups. The part is shown in Figure 5.6, and evaluated for two alternative cyclic process plans indicated. The test article is an ideal fit for hybrid manufacturing and serves the purpose of study here.

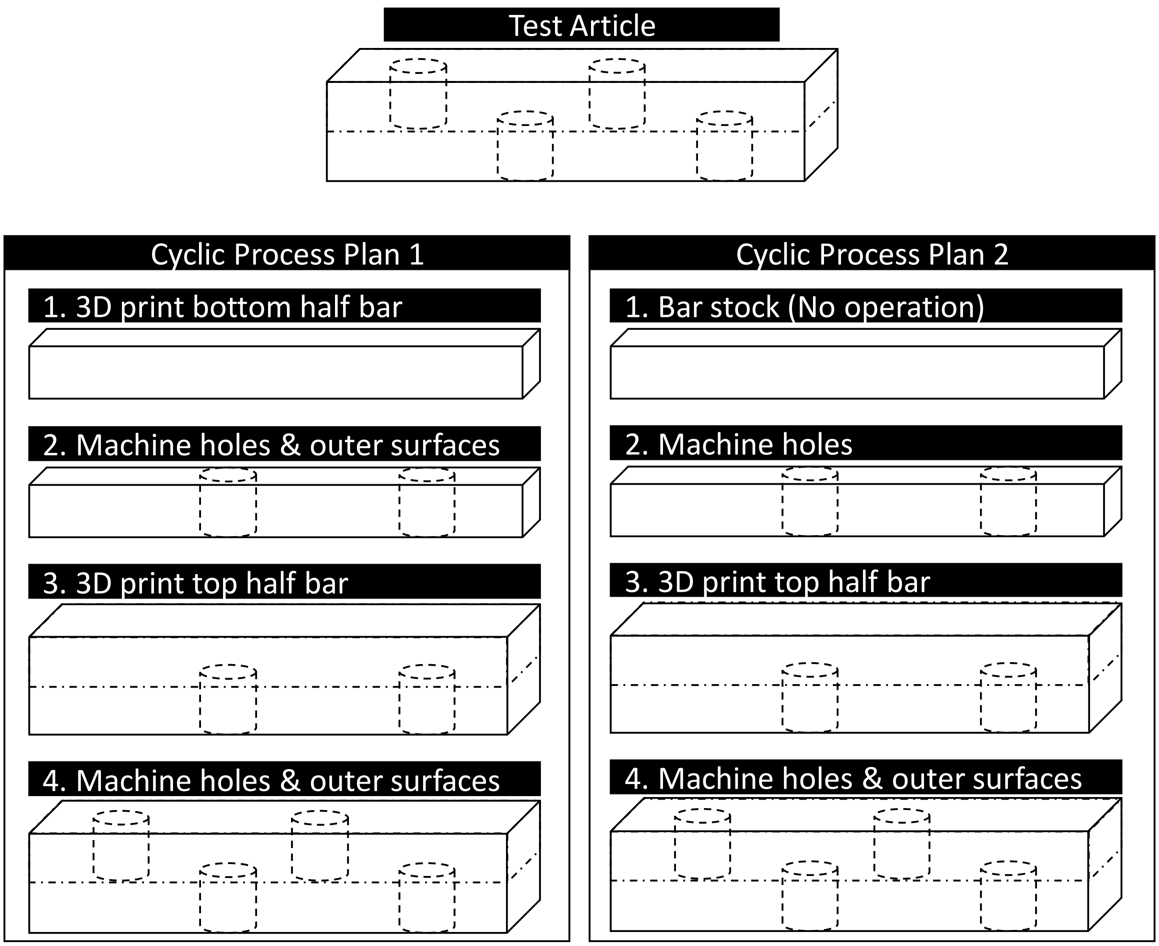

Figure 5.6: Test article (top) and cyclic process plans (bottom) to evaluate baseline 1

Nine test components with varying complexity, including radio-controlled (RC) airplane components, shown in Figure 5.7, are fabricated using the DE-HASM process to help answer the questions posed for Baselines 2, 3, and 4. Part complexity in additive manufacturing has been defined in a number of different ways, e.g., undercuts (features requiring support structure), deep microchannels, blind holes, twisted and contorted shapes, part volume to bounding volume ratio, feature scale ratio, and number of internal features [74–76]. Savonen [76] used surface area to volume ratio as a measure of complexity while evaluating the various impacts on sustainability performance of the fused deposition modeling (FDM) additive manufacturing process. Conner et al. [74] developed a reference system that describes the attributes of a product based on three manufacturing criteria: complexity, customization, and production volume. This approach facilitates product development decisions, and enables matching products and potential additive manufacturing processes. The authors considered part designs with higher surface area to volume ratios to be more geometrically complex. Surface area to volume ratio is considered here as a measure of part complexity.

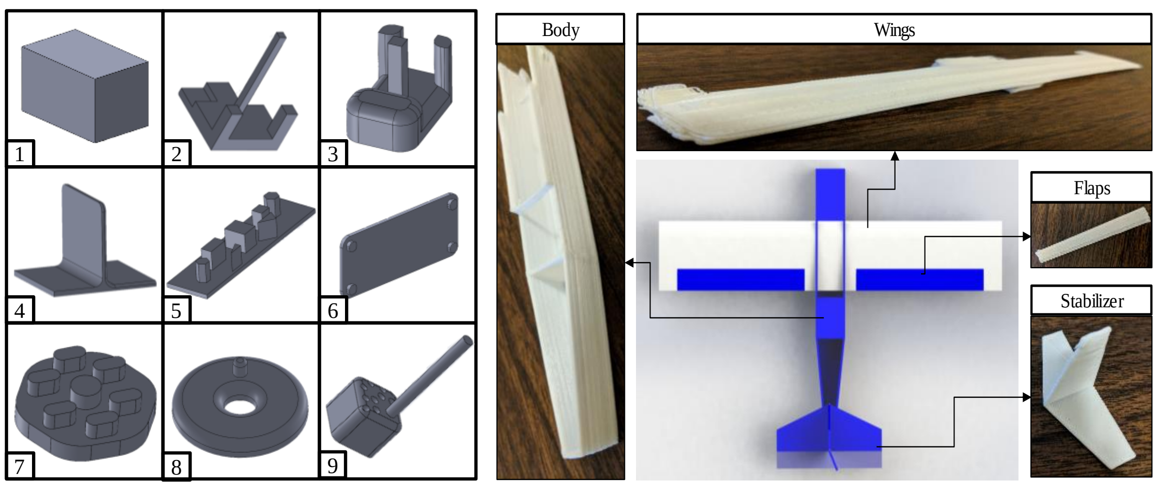

Figure 5.7: Nine test components (left) and RC plane components (right) fabricated using the DE-HASM process

Figure 5.8 illustrates the energy monitoring setup for collecting data in the DE-HASM process. Real-time energy consumption was measured using ONSET HOBO four-channel analog dataloggers coupled with three 10-100 amp split-core AC current transducers (CTs) [77]. CT 1 is used to measure energy consumed by the spindle motor, CT 2 is used to measure energy consumed by the two extruder motors and heater blocks, and CT 3 is used to measure energy consumed by the motors that provide x, y, and z axis motion.

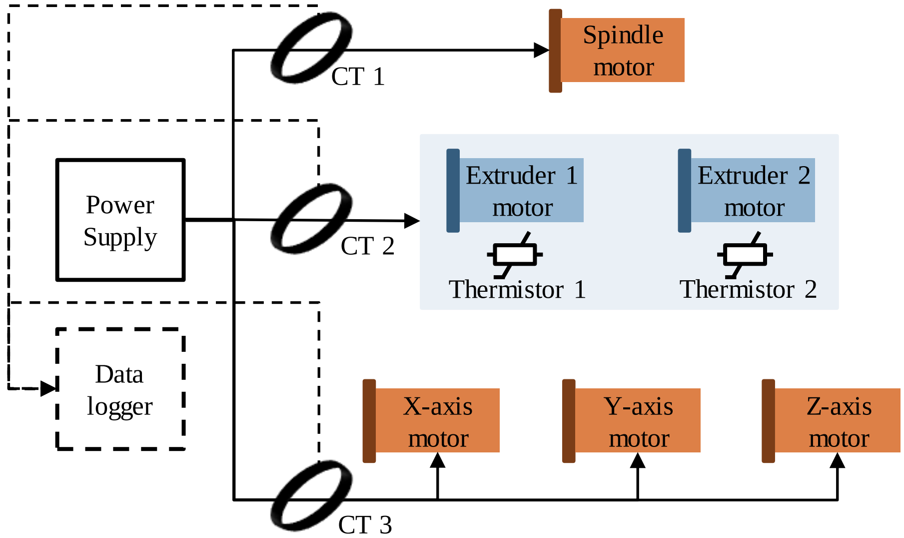

Figure 5.8: Energy monitoring setup for data-collection

Figure 5.9 shows the experimental setup of the DE-HASM process along with the energy monitoring system components.

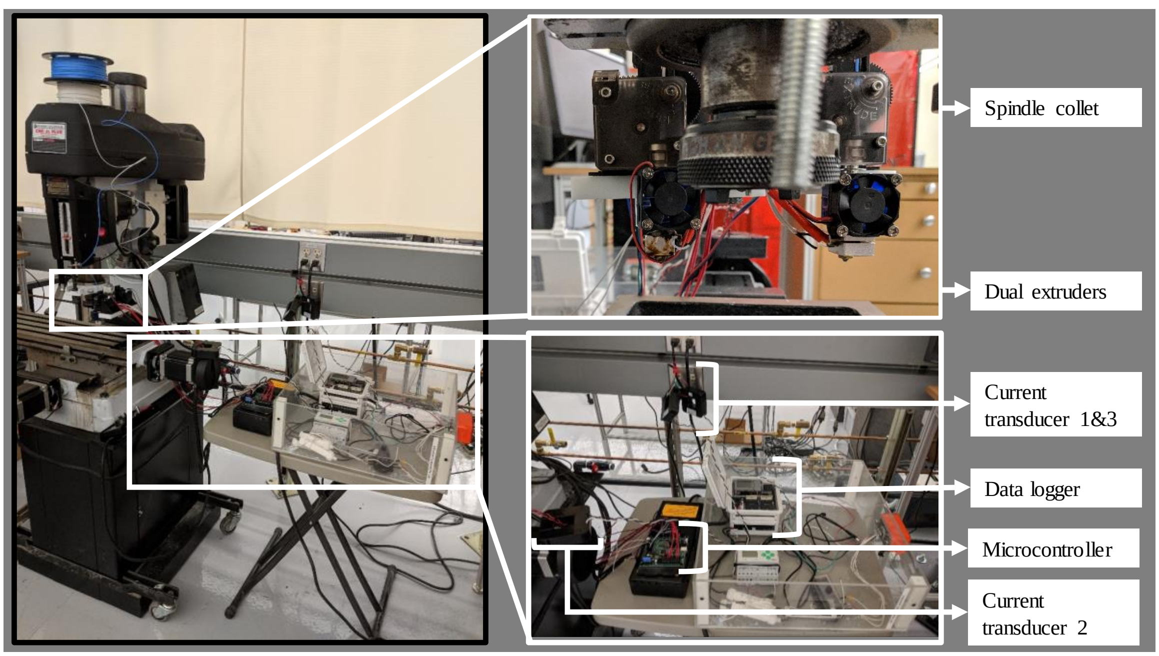

Figure 5.9: DE-HASM process experimental setup

5.5.2 Effectiveness of the Standards-Based Cyclic Model

The first baseline to test model effectiveness is the *ability to evaluate process plans of cyclic processes and identify low performing cycles and cycle operations*. To test this baseline, the two alternative cyclic process plans were evaluated for the test article shown in Figure 5.6 above. Figure 5.10 shows the results of the analysis. It can be seen that Cyclic Process Plan 1 consumes more energy than Plan 2. Under Plan 1, Operations 2 and 4 (both machining processes) consume the most process energy, while in Plan 2, Operation 4 (also a machining process) consumes the most energy. Eliminating a machining subprocess operation in Cyclic Process Plan 2 would support energy efficiency decision making. The cyclic model enabled evaluating subprocess energy use in each cycle for multiple cycles, utilizing a single mechanistic model for each subprocess (fused filament fabrication and CNC machining). Results of the first baseline supports the claim in Chapter 1 that the mechanistic behaviors of each subprocess must be accurately quantified to continuously improve process performance metrics.

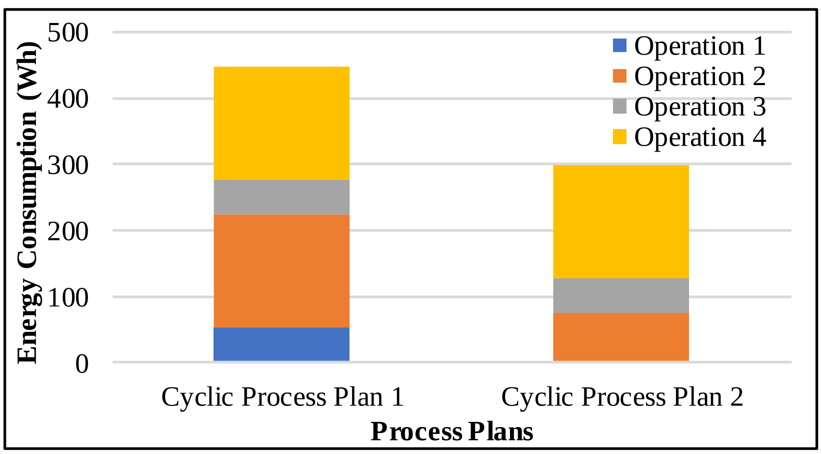

Figure 5.10: Energy consumption of cyclic process plans

The second baseline to test model effectiveness is model accuracy, which is determined as the percentage error between model-predicted and experimentally-determined process energy consumption. The accuracy of the cyclic model was consistent for parts of varying complexity. The nine test components had an average error of 15.06% (with a range of 6-29%) and the RC plane components had a similar average error (16.57%), whereas the RC plane components had a slightly smaller range (11-31%).

Effectiveness of the standards-based cyclic model for evaluating energy consumption in a hybrid manufacturing process for the third baseline, *ability to identify a correlation between process energy consumption and part complexity*, is presented in Figure 5.11.

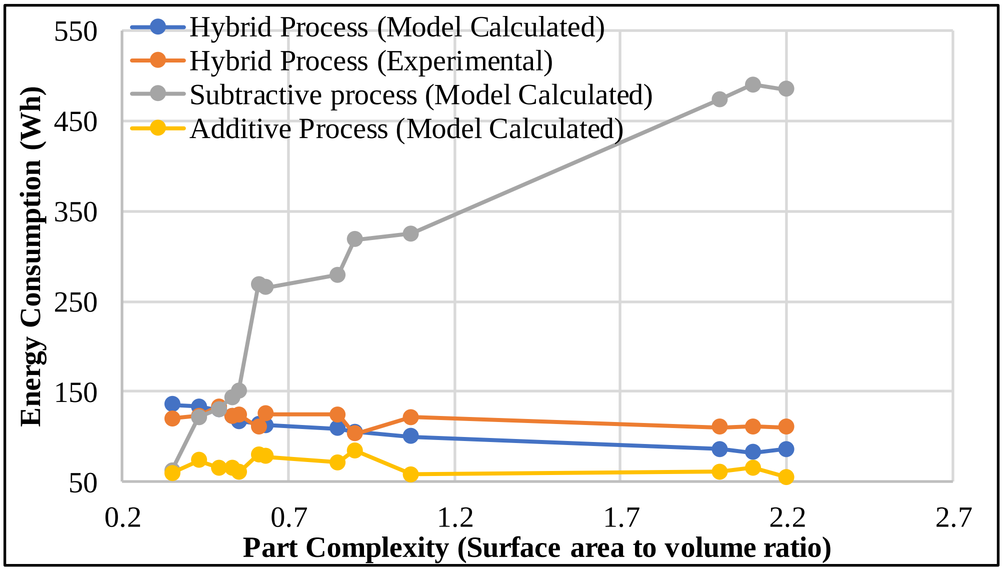

Figure 5.11: Correlation between process energy consumption and part complexity for nine test components and RC plane parts using the cyclic model

In Figure 5.11, it can be noted that, with increasing part complexity (surface area to volume ratio), energy consumption steadily decreases for the hybrid process, while subtractive process energy is seen to increase with complexity. Thus, a level of complexity exists where it is advantageous to switch from milling to hybrid (here, between 0.3 and 0.5).

The effectiveness of the standards-based cyclic model for evaluating energy consumption in a hybrid manufacturing process for the third baseline, *ability to identify a correlation between subprocess energy consumption and part complexity*, is presented in Figure 5.12. It can be noted that as complexity increases, energy consumed by the subtractive subprocess decreases, while additive subprocess energy consumption increases. This makes hybrid manufacturing more efficient for highly complex parts, supporting the results in Figure 5.9. Similar to the discussion made for Baseline 1, the cyclic model enabled evaluating subprocess energy use in each cycle for multiple cycles, utilizing a single mechanistic model for each subprocess (fused filament fabrication and CNC machining) and enabling energy efficiency decision making.

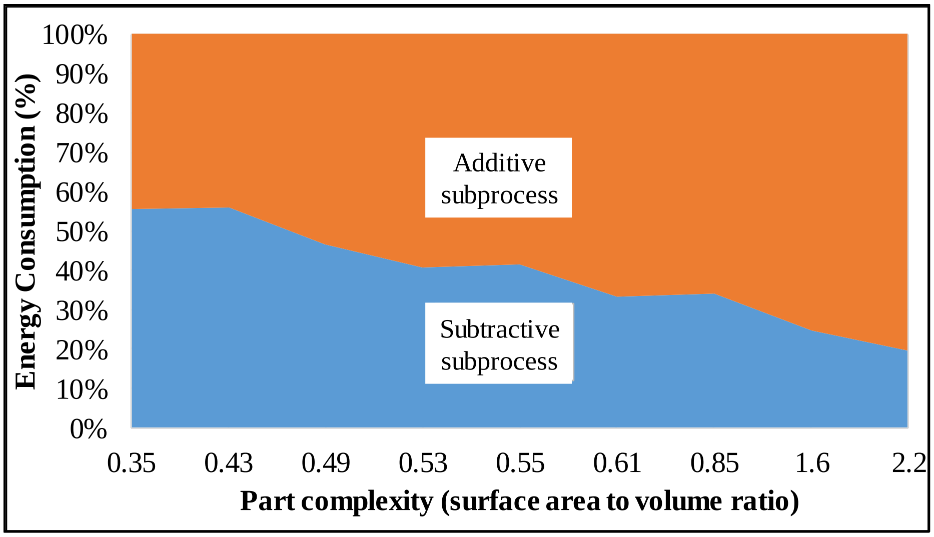

Figure 5.12: Correlation between hybrid subprocess energy consumption and part complexity for nine test components and RC plane parts using the cyclic model

5.6 Summary

In this research, the effectiveness of a standards-based cyclic model for characterizing hybrid manufacturing process energy consumption is evaluated. Developers and users of polymer-based hybrid manufacturing technologies can utilize the cyclic model to develop energy saving strategies during process development, product design, and process planning activities. The cyclic model developed for the DE-HASM process in Section 5.4.2 answers the first research question: *How can the ASTM E3012-16 standard be applied to facilitate environmental impact characterization of hybrid manufacturing processes?* In particular, from the research, it was shown that the ASTM standard can be applied to cyclic processes, allowing process energy use to be characterized and reduced.

The second research question: *How can the effectiveness of the developed cyclic model be evaluated?* is answered by developing four baselines for evaluating model effectiveness in Section 5.5. These baselines demonstrated that the modeling approach is able to evaluate process plans of cyclic processes and identify low performing cycles and cycle operations; exhibits an actionable level of accuracy; is able to identify a correlation between process energy consumption and part complexity; and is able to identify a correlation between subprocess energy consumption and part complexity.

Further insights and conclusions drawn from this research is presented in Chapter 6.

CHAPTER 6. SUMMARY AND CONCLUSIONS

This chapter summarizes the research tasks undertaken and reported in this thesis. Further, it briefly highlights the learnings derived from this research, research contributions, and opportunities for future work.

6.1 Summary

With the growing adoption of cyclic manufacturing processes as an alternative to conventional unit processes and sequential process flows, it is necessary for developers and users of these technologies to incorporate broader sustainability considerations during process development, product design, and process planning activities. However, characterization of cyclic manufacturing processes, such as hybrid process, is a challenge due to the complex, integrated, cyclic nature of subprocesses, which require a higher level of information synthesis than individual processes. Hence, the research reported herein was undertaken to facilitate sustainability characterization of cyclic manufacturing processes by developing a manufacturing process modeling framework and an information modeling framework. Achieving this goal enabled the modeling of hybrid manufacturing process and advance the sustainability evaluation of cyclic manufacturing processes.

This thesis work attempted to address the research objective through the following tasks:

- A manufacturing process modeling framework based on the ASTM 3012-16 standard [22] was developed to facilitate sustainability performance characterization of cyclic manufacturing processes. The framework enabled characterization, assessment, and extraction of product and process sustainability information of cyclic processes through model reusability, extensibility, and composability.
- An information modeling framework was developed based on the standard, information modeling guidelines suitable for application of the framework in assessing the sustainability performance of composed manufacturing systems were reported, and a software application based on the framework and information modeling guidelines was constructed for a prototype hybrid manufacturing process.

- The developed frameworks were utilized to characterize environmental performance of hybrid manufacturing processes. Baselines were drafted to evaluate the effectiveness of the developed standards-based cyclic model for characterizing energy consumption in a hybrid manufacturing process

6.2 Conclusions

Learnings from this research support sustainability characterization of cyclic manufacturing processes in several ways:

- Review of prior work on cyclic processes established the growth of the technology as an alternative to conventional unit processes and sequential process flows and accentuated the need for sustainability characterization.
- A manufacturing process modeling framework based on the ASTM 3012-16 standard enabled characterization, assessment, and extraction of product and process sustainability information of cyclic manufacturing processes.
- Adopting an information modeling principle (i.e., object-oriented programming) in developing a software framework enabled model reusability, extensibility, and composability.
- Developing a cyclic model based on the frameworks enabled environmental impact characterization of a hybrid manufacturing process.

Further, evaluating the effectiveness of the standards-based cyclic model using four baselines indicates that the cyclic model is effective in characterizing energy consumption in a hybrid manufacturing process. Specifically:

- Baseline 1: The cyclic model enabled evaluation of subprocess energy use in each cycle for multiple cycles utilizing a single mechanistic model for each subprocess (i.e., fused filament fabrication and CNC machining) and supported energy efficient process decision making.
- Baseline 2: The accuracy of the cyclic model was consistent for parts of varying complexity with an average error of 15.75% (6-31%).

- Baseline 3: The cyclic model enabled evaluation of energy consumption for different processes (hybrid, subtractive, and additive) with respect to part complexity and established a correlation between energy consumption and complexity for the different processes.
- Baseline 4: The cyclic model enabled evaluation of energy consumption of the two subprocesses (fused filament fabrication and CNC milling) in a hybrid manufacturing process with respect to part complexity and established a correlation between energy consumption and complexity for the two subprocesses.

6.3 Contributions

Various mechanistic and empirical models have been developed in prior literature for additive manufacturing process, but none have been reported for hybrid or cyclic processes. For example, Nagarajan [75] developed mechanistic and empirical models for several additive processes (i.e., fused deposition modeling, selective laser melting and stereolithography). His research lacked a uniform methodology to characterize additive or hybrid processes exhibiting cyclic nature. Such a uniform methodology is required to ensure consistency in characterizing cyclic manufacturing processes in a computer interpretable way and support the development of tools to improve the decision support capabilities, which research herein provides.

Specifically, the contributions of the work presented in this research include:

Contribution 1: Mathematical models presented in Chapter 3 enable characterization of energy use in a polymer-based hybrid manufacturing process. Developers and users of polymer-based hybrid manufacturing technologies can utilize the models to develop energy saving strategies during process development, product design and process planning activities. Overall, the mathematical models provided a deeper understanding of energy consumption in a hybrid process which aided to contribution 2 and 3.

Contribution 2: In order to effectively quantify sustainability metrics in the rapidly growing space of cyclic manufacturing, the development of supporting manufacturing process modeling and information modeling framework is essential. In particular, there is a deficiency in methodologies used to assess cyclic processes that this research aimed to remedy. The manufacturing process modeling framework reported in Chapter 3 provides terminology and mathematical representation for defining and storing product and process sustainability information of cyclic processes. An UMP quantification and aggregation algorithm was provided to store and evaluate sustainability metric information for cyclic manufacturing processes. Developers and users of cyclic manufacturing processes can utilize the modeling approach to develop energy saving strategies during process development, product design, and process planning activities.

Contribution 3: The developed unified information modeling framework in Chapter 4 enables UMP model developers and analysts to create and compose information models for performing sustainability characterization of manufacturing processes and systems. Information modeling guidelines were presented to help realize the framework, and provide step-by-step instructions for model developers to construct and compose information models using white box design methods. Further, the guidelines provide instructions to UMP performance analysts for utilizing black box design principles to analyze composed models for evaluating product design alternatives. An application of the framework was demonstrated for a hybrid manufacturing process composed of additive (FFF) and subtractive (CNC milling) processes.

6.4 Opportunities for Future Work

In completing this research, several opportunities for future work were identified, which include:

Opportunity 1: In Chapter 4, an information modeling framework and application were developed to compose models of two unit manufacturing processes. Further, a software framework was provided to compose multiple unit manufacturing processes that form a process flow. Future research can consider developing a software application using the information modeling framework for sustainability performance assessment of process flows. In addition, integrating the software application with the IoT technology and neural network modeling methods mentioned above for a hybrid manufacturing system would provide a smart manufacturing approach, utilizing end-to-end data collection, processing, and analytics for improving product and process sustainability performance.

Opportunity 2: The cyclic model for a polymer-based hybrid process developed in Chapter 5 includes sustainability impacts of the manufacturing stage, and excludes impacts of other stages, such as raw material extraction, raw material processing, and product end of life. Comparing the environmental impacts of remanufactured polymer parts produced using the hybrid system with recycled polymer parts using a non-hybrid system could further accentuate the need for hybrid processes. This can be accomplished by performing life cycle analysis involving all cradle-to-grave stages.

Opportunity 3: Data collected to evaluate the cyclic model in Chapter 5 is limited to a prototype polymer-based hybrid manufacturing process developed at Oregon State University. To more accurately evaluate energy use in polymer-based hybrid processes, experimental studies should be performed with other hybrid processes. This can be accomplished by: 1) utilizing Internet of Things (IoT) technology to connect, collect, and exchange data among available processes, and 2) applying neural network models to accurately predict energy use based on the data collected from the various hybrid processes.

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