AN ABSTRACT OF THE DISSERTATION OF

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Title: Integrated Manufacturing Process and System Analysis to Assist Sustainable Product Design

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Product development in the 21st century requires integrating sustainability performance evaluation with product design and manufacturing activities. A variety of factors, including climate change, public awareness, and increasingly strict regulations have compelled companies to design and manufacture more sustainable products. While the design phase typically accounts for only 5-7% of a product’s cost, 70-80% of product life cycle costs are determined (or locked in) during design, for example due to the consumption of materials and other resources. In addition to financial costs, however, environmental and social costs are similarly set during product design. Thus, the decisions made during the design phase have a significant impact on the life cycle

sustainability performance of a product. To improve product sustainability performance, it has been recognized that supply chain and manufacturing activities should be analyzed during the design phase. Supporting methodologies and tools have been developed to aid in evaluating sustainability performance during product design phase. However, these existing methods and tools are often developed for domain experts and not well-suited for educating non-expert decision makers (e.g., engineering students and engineering practitioners), who do not possess specialized knowledge in sustainability analysis of product designs and manufacturing processes, for several reasons. First, relating sustainability information to conceptual product designs is challenging. Second, eco-design software tools often require costly licensing and training, limiting their ease of access. Third, domain expertise (e.g., knowledge of eco-design and manufacturing methods and tools) and extended analysis times are required to produce meaningful results. Thus, the objective of the research presented herein is to facilitate simultaneous analysis of sustainability performance impacts of different manufacturing processes and systems through unit manufacturing process modeling within an easy-to-use, publicly-available product design and manufacturing analysis tool. To achieve the objective of this research, a framework is developed that considers a cradle-to-gate life cycle scope consisting of four phases: (1) product development, (2) supply chain configuration, (3) manufacturing process design, and (4) manufacturing process and system sustainability analysis. To implement this sustainability assessment framework and to address the identified limitations of sustainability assessment tools, a proof-of-concept Manufacturing Process and System (MaPS) Sustainability Analysis Tool is developed. The proof-of-concept tool is

implemented as spreadsheet models (MS Excel) comprising four modules, each mapping to a phase of the developed framework. In addition to environmental impacts, the tool can be used to investigate economic and social impacts. These analyses are demonstrated by quantifying energy and associated carbon footprint, the cost of goods sold, and worker safety, respectively. Further, the operational performance of the MaPS Sustainability Analysis Tool was evaluated in terms of ease-of-use and usefulness metrics by undergraduate and graduate engineering students at Tampere University (Finland) and Oregon State University (USA). Study participants found the tool easy-to-use and indicated it would be useful in the task of analyzing the product design, supply chain, and manufacturing process sustainability performance (i.e., environmental, economic, and social impacts). Several opportunities for future work have been identified to build upon the research undertaken as a part of this dissertation. First, the framework developed herein can be expanded to include other phases of the product life cycle. In addition, key software tool operational characteristics and graphical user interfaces should be investigated to improve efficiency, effectiveness, satisfaction, and learnability of the MaPS Sustainability Analysis Tool, especially by engaging broader and more representative groups of users. To improve tool flexibility and functionality, numerical models of different unit manufacturing processes should be developed, validated, and implemented for sustainability assessment of manufacturing process and systems.

Integrated Manufacturing Process and System Analysis to Assist Sustainable Product Design

by
Kamyar Raoufi

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

Kamyar Raoufi, Author

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the sustenance that life could offer, and without them I would never be where I stand today. I am forever thankful to them and I appreciate their sacrifice. I hope I can return even a small portion of their devotion. This work could not have been completed without the energy and motivation I gained from seeing and hearing them, albeit from far away.

CONTRIBUTION OF AUTHORS

The work comprising this dissertation was done under two funded projects as well as during an industry internship. This work has involved several collaborators, and has been published in peer-reviewed conference proceedings and journal articles as described in Chapter 1. However, this dissertation reports only on the research conducted by its author, Kamyar Raoufi. As such, the dissertation is presented in standard thesis format, rather than a manuscript format, to clarify the contributions of the research.

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NOMENCLATURE

A_{part}	Projected area of the part
c_j	Empirical constant
c_{pm}	Heat capacity of the metal powder
c_{pi}	Heat capacity of ith binder component
DAW_{mfg}	Days away from work for manufacturing
DAW_{trans}	Days away from work for transportation
d_{cl}	Clearance between mold and part
d_{cav}	Depth of the mold cavity
$E_{clamping}$	Cooling energy consumption
E_{cool}	Cooling energy consumption
$E_{injection}$	Cooling energy consumption
E_{MIM}	Injection molding (IM) energy use
E_{mat_inj}	Material injection energy consumption
E_{melt}	Melting energy consumption
E_{pack}	Packing energy consumption
E_{reset}	Resetting energy consumption
$E_{basic(IM)}$	Basic energy for IM
E_{total}	Total energy consumption per part
H_{cool}	Heat to be removed from the molded part
H_{fi}	Heat of fusion for the ith binder component
H_m	Heat of fusion for the metal powder
h_{max}	Maximum wall thickness of the part

L_s	Maximum clamp stroke of the machine
m	Mass of feedstock
$MDAW_{mfg}$	Median days away from work for manufacturing
$MDAW_{trans}$	Median days away from work for transportation
n_{cav}	Number of cavities in the mold
N_{trans}	Number of parts that can be transported by each vehicle
$NOII_{mfg}$	Nonfatal occupational injuries and illnesses for manufacturing
$NOII_{trans}$	Nonfatal occupational injuries and illnesses for transportation
p_{inj}	IM machine injection pressure
$P_{basic(IM)}$	Basic power of IM machine
P_{inj}	IM machine injection power
PV	Production volume
Q_{max}	Maximum material flow rate
Q_{avg}	Average material flow rate
$RDAW_{mfg}$	Rate of days away from work for manufacturing
$RDAW_{trans}$	Rate of days away from work for transportation
$RNOII_{mfg}$	Rate of nonfatal occupational injuries and illnesses for manufacturing
$RNOII_{trans}$	Rate of nonfatal occupational injuries and illnesses for transportation
$t_{basic(IM)}$	Basic IM time
$t_{cycle(IM)}$	IM cycle time
t_c	Cooling time
t_{dry}	Dry time
t_{dwell}	Dwell time

t_i	Injection time
t_{mfg}	Manufacturing process time
t_r	Resetting time
t_{trans}	Transportation time
T_{ej}	Ejection temperature
T_{amb}	Ambient air temperature
T_m	Mold temperature
T_{inj}	Injection temperature
V_{binder}	Volume of the binder
V_i	Volume of i^{th} binder component in shot
V_m	Volume of metal powder in shot
V_{part}	Volume of the part
V_{shot}	Volume of the shot
X_b	Mass fraction of binder
X_m	Mass fraction of metal powder
α	Coefficient of thermal expansion
ε	Volumetric shrinkage
γ	Thermal diffusivity of the material
λ_f	Thermal conductivity of the feedstock
η_{cool}	Energy efficiency of cooling
η_{inject}	Energy efficiency of injection
η_{melt}	Energy efficiency of melting
η_{pack}	Energy efficiency of packing

η_{reset}	Energy efficiency of resetting
ρ_b	Density of the binder
ρ_i	Density of the i^{th} binder component
ρ_m	Density of the metal powder
Δ	Fraction of part volume in the gating system

Chapter 1: INTRODUCTION

1.1 Motivation

Product development in the 21st century requires integrating sustainability performance evaluation with product design and manufacturing activities. A variety of factors, including climate change, public awareness, and stricter regulations have compelled companies to design and manufacture more sustainable products [1]. While the design phase cost account for only 5-7% of the entire product cost, 70-80% of the total product cost including material and resource consumption is determined in this phase [2]. A parallel situation could be hypothesized for the environmental impacts [1]. This indicates the significant impact of the design phase on the sustainability performance. To investigate sustainable product design, activities from the supply chain level and manufacturing level should be analyzed [3].

Eco-design tools, such as Granta CES EduPack [4], SolidWorks Sustainability [5], Sustainable Minds [6], OpenLCA [7], IDEMAT [8], SimaPro [9], and GaBi [10] as well as CAD-integrated LCA tools [11–13] have been developed for decision makers to implement sustainable design and manufacturing assessment. In their review of the literature over the last twenty years, Rossi et al. [14] identified the barriers preventing the effective use of eco-design methods and tools in industry and to provide recommendations and solution approaches to overcome them. They reiterated the need for education and training of the workforce in eco-design methods and tools.

As mentioned above and discussed in details in Chapter 2, experts are well-equipped with methodologies and software tools to conduct product and manufacturing sustainability assessments. However, conducting such assessments is challenging for *non-expert decision-makers (e.g., engineering students and engineering practitioners), who do not possess specialized knowledge in sustainability analysis of product designs and manufacturing processes*, due to the multidisciplinary nature of sustainability [15]. One enabler to address this issue is engineering education [16–19]. This is also pinpointed in the third ABET criteria describing student outcomes: *an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability* [20].

Educators have previously incorporated sustainability principles into engineering courses and also have developed individual courses or curricula on sustainability topics. They have developed a variety methodologies [21–32], which will be discussed later in Chapter 2, and applied various *ad hoc* approaches, such as critique from graduate student coaches for undergraduate course and group projects [33], integrating guided-discovery instruction into undergraduate mechanical engineering courses [34], planning a sustainable manufacturing option for manufacturing engineering curricula [35], integrating sustainability-related competencies (e.g., responsibility, future orientation, and action skills) in the competence schemes of bachelor programs [36], creating course sequences for sustainability using a developmental approach based on Bloom's Taxonomy [37], and using software tools to teach sustainability concepts [38].

However, there is a need to develop methods and software tools to assist non-expert decision makers in sustainable product design and manufacturing [18].

1.2 Limitations of Prior Work

As will be discussed in details in Chapter 2, methodologies and tools have been developed for experts to evaluate sustainability performance metrics for manufacturing processes during product design phase. However, existing methods and tools are not well-suited for educating non-expert decision makers about sustainable engineering due to the following reasons. First, relating sustainability information to the product conceptual design is challenging for non-experts [39]. Second, the eco-design software tools often require costly licensing and are not easy to access [40,41]. Third, domain expertise (knowledge of eco-design issues and existing eco-design tools) and extended analysis times are required to produce meaningful results [14].

Next, a deficiency of LCA tools in performing manufacturing analysis is, in general, that they rely on product mass to quantify manufacturing processes environmental impacts. Thus, it is difficult to effectively investigate the impacts of product design changes on processes, especially when product mass or process parameters experience little to no change. While methods and software tools have been developed to quantify the impacts of one or two pillar(s) of sustainability, there is a need for methods and software tools capable of conducting quantitative assessment of all the three pillars of sustainability during the product design phase [42]. Finally, software tools are needed which are simple and user-friendly [43].

1.3 Problem Statement

As evidenced from the foregoing, a unit manufacturing process model-based approach is needed to assist non-expert decision makers in quantifying and evaluating the impacts of product design changes on the sustainability performance of manufacturing processes and systems.

1.4 Research Question

How can a unit manufacturing process model-based approach be used by non-experts during product design to quantify and evaluate the sustainability performance of manufacturing processes and systems?

1.5 General Hypothesis

Implementation of standards-based unit manufacturing process models within an easy-to-use, publicly-available manufacturing process and system sustainability analysis tool will enable sustainability performance assessment of manufacturing processes and systems.

1.6 Research Objective

The objective of the research presented herein is to facilitate simultaneous analysis of sustainability performance impacts of different manufacturing processes and systems through unit manufacturing process modeling within an easy-to-use, publicly-available manufacturing process and system sustainability analysis tool.

1.7 Research Tasks

To fulfill the research objectives, four main tasks detailed below were undertaken in the research presented herein.

- Task 1: Identifying the relevant methods and software tools for analyzing product design, supply chain, and manufacturing process sustainability performance (i.e., environmental, economic, and social impacts);
- Task 2: Establishing a framework that integrates product design and supply chain information within a mechanistic unit manufacturing process modeling approach for quantifying manufacturing sustainability performance;
- Task 3: Developing a publicly-available manufacturing process and system sustainability analysis tool for non-experts to conduct manufacturing process and system analysis under the lens of sustainability performance; and
- Task 4: Evaluating the operational performance of the manufacturing process and system sustainability analysis tool in terms of the ease-of-use and usefulness metrics.

1.8 Contribution of this Research to the Literature

To summarize the dissertation research completed, its contributions to the published research is presented in Table 1 with respect to each of the four research tasks presented above. The roles of fellow student authors are also noted. In each paper, the role of the faculty co-authors was to provide input and direction of the work as well as helpful review and feedback.

Table 1. Contribution of this research to the published literature

Source (†Corresponding; *Student)	Contribution of this Dissertation Research	Task
Alsaffar, A. J.*, **Raoufi, K.**, Kim, K.-Y., Kremer, G. E. O., and Haapala, K. R.†, 2016, “Simultaneous Consideration of Unit Manufacturing Processes and Supply Chain Activities for Reduction of Product Environmental and Social Impacts,” Journal of Manufacturing Science and engineering, 138, pp. 101009.1-101009.18 (ref. [44])	The literature review conducted on the social aspect of sustainability supported the discussion of prior work in the paper.	1
	The four social impact metrics developed in this research, relative to transportation and manufacturing processes, supported the sustainability assessment performed.	3
	This dissertation work extended M.S. thesis work by Ahmed Alsaffar, which made up the bulk of the paper.	-
Raoufi, K.†, Wisthoff, A. K.*, DuPont, B. L., and Haapala, K. R., 2019, “A Questionnaire-Based Methodology to Assist Non-Experts in Selecting Sustainable Engineering Analysis Methods and Software Tools,” Journal of Cleaner Production, 229, pp. 528–541 (ref. [41])	The review of methods and software tools developed for conducting sustainable engineering assessment supported the literature review in the paper.	1
	The product data and information gathered under this research (for multicopters) was used to demonstrate the sustainable assessment approach developed in the paper.	3
	The four social impact metrics developed in this research, relative to transportation and manufacturing processes, supported the sustainability assessment performed.	3
	This dissertation work added to work under a class team project with Addison Wisthoff.	-
Raoufi, K.†, Park, K.*, Hasan Khan, Md. T.*, Haapala, K. R., Psenka, C. E., Jackson, K. L., Kremer, G. E. O., and Kim, K.-Y., 2019, “A Cyberlearning Platform for Enhancing Undergraduate Engineering Education in Sustainable Product Design,” Journal of Cleaner Production, 211, pp. 730–741 (ref. [45])	The review of existing methods and software tools for evaluating economic, environmental, and social impacts of manufacturing during product design supported the discussion of the literature in the paper.	1
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the learning platform and pilot project reported in the paper.	4
	This dissertation work paired with tools developed by Kijung Park (supply chain analysis) and Md. Tarique Hasan Khan (design visualization) from Pennsylvania State University and Wayne State University	-

Raoufi, K.†, Haapala, K. R., Jackson, K. L., Kim, K.-Y., Kremer, G. E. O., and Psenka, C. E., 2017, "Enabling Non-Expert Sustainable Manufacturing Process and Supply Chain Analysis During the Early Product Design Phase," Procedia Manufacturing, pp. 1097–1108 (ref. [26])	The review of existing methods for evaluating environmental impacts of supply chain configurations during product design supported the discussion of the literature in the paper.	1
	Phase 2 of the framework developed herein was reported as a way to support non-experts in quantifying the environmental impacts of supply chain configurations during product design phase.	2
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the environmental impact assessment reported in the paper.	3
Raoufi, K.†, Manoharan, S.*, and Haapala, K. R., 2019, "Synergizing Product Design Information and Unit Manufacturing Process Analysis to Support Sustainable Engineering Education," Journal of Manufacturing Science and Engineering, 141(2), pp. 021018–021032 (ref. [46])	The review of unit manufacturing process modeling for evaluating environmental impacts of manufacturing during product design as well as existing methods in sustainable product design using design repositories supported the discussion of the literature in the paper.	1
	Phase 1 of the framework developed herein was reported as a way to support non-experts in sustainable product design considering economic and environmental impacts.	2
	The product data and information gathered under this research (for multicopters) was used to demonstrate the approach developed in the paper.	3
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the environmental impact assessment reported in the paper.	3
	This dissertation work formed the scientific basis for the methodology and provided the case study for this paper. Sriram Manoharan authored text for the background and developed a process selection method, which are not included herein.	-
Khan, M. T. H.*, **Raoufi, K.**, Park, K.*, Reza, T.*, Psenka, C. E., Jackson, K. L., Haapala, K. R., Kremer, G. E. O., and Kim, K.-Y., 2017, "Development of Learning Modules for Sustainable Life Cycle Product Design: A Constructionist Approach," Proceedings of the ASEE Annual Conference & Exposition, Columbus, Ohio, p. 14 (ref. [32])	The review of existing methods and software tools for evaluating environmental impacts of manufacturing during product design supported the discussion of the literature in the paper.	1
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the learning platform and pilot project reported in the paper.	3
	This dissertation work paired with tools developed by Kijung Park (supply chain analysis) and Md. Tarique Hasan Khan and Tasnia Reza (design visualization) from Pennsylvania State University and Wayne State University.	-

Raoufi, K. †, Haapala, Karl. R., Kremer, G. E. O., Kim, K.-Y., Psenka, C. E., and Jackson, K. L., 2017, "Enabling Cyber-Based Learning of Product Sustainability Assessment Using Unit Manufacturing Process Analysis," Proceedings of the ASME 2017 IDETC/CIE Conference, ASME, August 6-9, Cleveland, Ohio, USA, p. V004T05A038 (10 pp.) (ref. [38])	The review of unit manufacturing process modeling and existing methods for evaluating environmental impacts of manufacturing during product design supported the discussion of the literature in the paper.	1
	Phase 3 of the framework developed herein was reported as a way to support non-experts in quantifying the environmental impacts of manufacturing processes during product design phase.	2
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the environmental impact assessment reported in the paper.	3
Raoufi, K.†, Taylor, C., Laurin, L., and Haapala, K. R., 2019, "Visual Communication Methods and Tools for Sustainability Performance Assessment: Linking Academic and Industry Perspectives," Procedia CIRP, Purdue University, West Lafayette, Indiana, USA, pp. 215–220 (ref. [47])	The direct input from sustainability assessment practitioners about visualization of sustainability analysis results in the proof-of-concept manufacturing process and system analysis tool developed herein supported the discussion of the literature in the paper.	4
Raoufi, K.† and K.R. Haapala, 2020, "A Cyber-based Environment for Learning Sustainable Product Design in Manufacturing Engineering Education," *The Internet and Higher Education* (Research Article, *in preparation*) (ref. [48])	The review of existing methods and software tools for evaluating economic, environmental, and social impacts of manufacturing during product design supported the discussion of the literature in the paper.	1
	The integrated sustainability assessment framework developed herein was reported as a way to support non-experts in quantifying the economic, environmental, and social impacts of supply chain configurations during product design phase.	2
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the economic, environmental, and social impact assessment reported in the paper.	3
	The proof-of-concept manufacturing process and system sustainability analysis tool developed herein supported the learning platform and pilot project reported in the paper.	4
Raoufi, K.†, D.S. Harper, K.R. Haapala, 2020, "Reusable Unit Process Life Cycle Inventory for Manufacturing – Metal Injection Molding," *Production Engineering Research and Development* (Research Article, *in revision*) (ref. [49])	The numerical model for metal injection molding developed for the proof-of-concept manufacturing process and system sustainability analysis tool was reported under the paradigm of the unit process life cycle inventory modeling method The metal injection molding unit process model was demonstrated for producing a diaphragm valve for application in the medical field	3

1.9 Delimitations

While the framework developed herein supports sustainable engineering education, the focus of this dissertation proposal is on the technical aspects of implementing unit manufacturing process modeling within an easy-to-use, publicly-available manufacturing process and system sustainability analysis tool [50]. While assessment of impacts of the approach on learning objectives and outcomes from in-class evaluation is outside the scope of this dissertation, it is being reported by the collaborating project team with which this research has been conducted [51].

1.10 Ph.D. Dissertation Outline

This dissertation is comprised of six chapters. An introduction to the research including motivation, limitations of prior work, objective, and delimitations are presented in Chapter 1. The literature review covering sustainability characterization of unit manufacturing processes, product design using design repositories, sustainability assessment methods and software tools, and limitations of prior work are presented in Chapter 2. Next, in Chapter 3, the framework developed in this research to create a publicly-available manufacturing process and system sustainability analysis tool is described. Demonstration of the application of the framework is presented in Chapter 4. The operational performance evaluation of the Manufacturing Process and System (MaPS) Sustainability Analysis Tool is presented in Chapter 5. Finally, the summary of the research and the opportunities for the future research are discussed in Chapter 6.

Chapter 2: LITERATURE REVIEW

Three areas of extant research provide a foundation for this work: (1) sustainability characterization of unit manufacturing processes, (2) product design using design repositories, and (3) sustainability assessment methods and software tools. Prior work for each of these areas are reviewed in Sections 2.1-2.3, respectively. The limitations of prior work are summarized in Section 2.4.

2.1 Sustainability Characterization of Unit Manufacturing Processes

The manufacturing sector accounts for approximately one-third of U.S energy consumption [52]. Hence, reducing energy consumption and associated energy costs through increased efficiency can help strengthen the economic vitality of U.S manufacturers, while also helping to protect our environment [53]. Manufacturing and sustainability are the two key aspects of engineering that promote innovation and industrial competitiveness through science, technology, and standards [54]. 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 [55]. Sustainable manufacturing has improved the performance of the industrial processes through innovation and technology to create complex, yet reliable and affordable products [56].

A manufacturing process is defined as any type of activity that uses some form of energy to transform material or intermediate products into an intended product [57]. A product can be manufactured in many ways, thus creating a diverse set of unit manufacturing processes (UMPs) alternatives and a need to evaluate the alternatives in terms of energy, materials, and other resources [58]. Garretson et al. [59] defined UMPs as *the smallest elements in manufacturing, which involve transformations to add value either from inputs or outputs, or with specific shape, structure, or property transformations*. For systematic analysis of manufacturing, a two-level approach based on LCA methodology was developed and reported, which combined the unit process life cycle inventory (UPLCI) effort and the CO2PE! Initiative [60,61]. These international efforts aim to provide manufacturing unit process datasets for supporting LCAs of products manufactured in multi-unit process plants. Many researchers have applied UPLCI to estimate the energy consumption and to represent the environmental life cycle impacts of different UMPs as presented in Table 2.

For a similar purpose of analyzing manufacturing process, researchers have investigated process-based methods enabling decision makers to assess product sustainability performance from the cradle-to-gate life cycle scope [44,62,63]. Impact of material removal rates on the specific energy consumption of a milling machine, for example, was investigated by Diaz et al. [64]. Similarly, a methodology to model the effect of machining process parameters on energy consumption was developed by Rajemi et al. [65] and illustrated for turning. These practices to compute and compare the sustainability performance of manufacturing processes are inconsistent, due to lack of uniform data, methods, and tools to represent manufacturing processes and equipment performance [57].

Table 2. UMPs investigated by applying UPLCI and CO2PE! approaches

Process	Environmental	Source
Drilling	Water footprint	[66]
	Energy consumption	[67]
	Energy and resource consumption	[61]
	Energy consumption	[68]
	Energy consumption	[69]
	Water footprint	[70]
Gas metal arc welding	Energy consumption	[71]
Grinding	Energy consumption	[72]
	Energy consumption	[73]
	Energy consumption	[74]
	Global warming, ecotoxicity, and abiotic resources depletion	[75]
Injection molding	Energy consumption	[76]
	Energy consumption	[77]
Laser cutting	Energy consumption	[77]
	Energy consumption	[69]
	Energy consumption and resource efficiency	[78]
	Energy consumption	[79]
	Energy consumption	[80]
Milling	Energy consumption	[77]
	Water footprint	[66]
	Water footprint	[70]
Stereolithography	Energy consumption	[81]
Turning	Energy consumption	[77]
	Water footprint	[70]
	Water footprint	[66]

To address the need for a uniform methodology to represent manufacturing processes, ASTM International has developed standards to assist in characterizing manufacturing processes for sustainability-related decisions. ASTM E3012-20, Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes [82], provides manufacturers an approach to characterize any category of manufacturing process and to systematically capture and describe relevant environmental information. It defines a process characterization method that uses graphical and formal representations to support the construction of unit manufacturing process (UMP) information models for characterizing the environmental aspects of manufacturing processes. The standard UMP information model (Figure 1) according to ASTM is comprised of four elements (i.e., inputs, outputs, product and process information, and resources) that support manufacturers in systematically identifying, collecting, structuring, and visualizing manufacturing information.

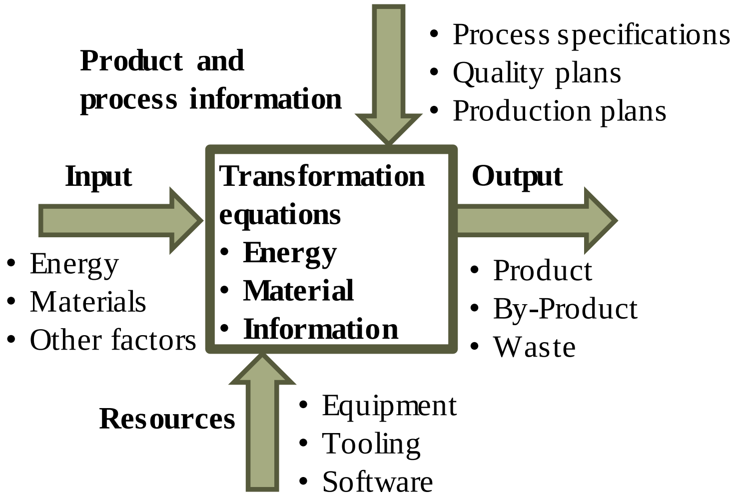


Figure 1. UMP model representation (adapted from ASTM [83])

A science-based reference for estimating energy consumption of unit manufacturing processes was developed by Madan et al. [76] based on ASTM E3012-16. It was illustrated for the injection molding process. Mani et al. [53] used ASTM E3012-16 to develop a methodology for sustainability characterization of additive manufacturing processes. An open web-based repository for capturing manufacturing process information was developed by Bernstein et al. [84], while Brodsky et al. [85] presented an architecture for managing a model repository and conducting analysis on manufacturing processes based on UMP models. These efforts have set the stage for ongoing and future work to develop engineering methods and tools for practitioners and learners to undertake product manufacturing sustainability assessment.

2.2 Product Design Concept Generation

A design repository provides an opportunity for researchers and designers to quickly and easily store and retrieve design knowledge and information. Different aspects of product information, such as materials, components, required manufacturing processes, and CAD models could be captured in a design repository. Some researchers have used design repositories in engineering and design education to teach students about the application of functional modeling early in the product design phase [86].

Takai and Du [87] developed an engineering uncertainty repository at the Missouri University of Science and Technology to help students gain a better understanding of uncertainty and to assist instructors to include uncertainty in their engineering courses. The authors evaluated the repository of teaching materials and website in five classroom settings. Their results demonstrated the successful development of the repository. Oman et al. [88] developed a methodology for the undergraduate students to contribute in generating innovative and creative concepts in the early phases of engineering design. The authors first investigated the factors that make a product innovative and, then, archived the findings in a repository of innovative products (RIP), as well as the Design Repository hosted at Oregon State University. They applied an interactive morphological matrix allowing students to generate conceptual designs based on the product functionality. The initial results in designing innovative products using the Design Repository integrated with the RIP, indicated a successful mapping of the innovation and the functions within products. Their study demonstrated the successful application of the design repository in an educational context, but did not integrate it with sustainability assessment.

Conversely, Gilchrest et al. [89] applied a design repository as a part of a broader sustainability assessment as a part of a research study. They explored whether innovative products have a lower environmental impacts compared to their common counterparts. They investigated six products that were identified as innovative by popular media, and then compared them with eight common counterparts having the same functionality. To conduct the life cycle assessment (LCA) study, the Design Repository at Oregon State University was applied to provide product design data. The authors [90] later expanded the approach by evaluating the environmental impacts of each component and function of the products, rather than relating the impacts to the product as a whole. This approach could be beneficial for teaching design for X (DfX) concepts.

In this way, design repositories can play a key role in improving the effectiveness of the product development process. For example, Haapala et al. [91] developed a five-step methodology to virtually create design alternatives based on product functionality. The approach applies an automated concept generator connected to the Design Repository at Oregon State University. They then utilized LCA to evaluate the environmental impacts of the conceptual designs and found that integrating LCA during conceptual design with the Design Repository has the potential to successfully indicate product environmental impacts based on the virtual concepts. However, the Design Repository has a limited set of products from which it can draw inferences and generate representative concepts. Familiarity with the repository would be needed to facilitate expansion of the database, while any further product analysis would require design refinement and use of external tools (e.g., LCA software).

Ramanujan et al. [92] developed the ShapeSift software tool for exploring 3D part repositories using part metadata such as materials, manufacturing processes, and functionality, to assist sustainability-aware decision making. The software computes and visualizes the integration of similarities in part attributes such as geometry, material, and manufacturing processes, along with the associated environmental impacts. The authors presented a prototype interface for sketch-based querying to explore the 3D part repository. The tool assumes the users have knowledge of the content of the repository, which is not suitable for decision makers. Wisthoff et al. [93] created an engine using a multi-layer neutral network to relate the LCA data of consumer products to product attributes such as volume, mass, number of parts, lifetime, and number of manufacturing processes. They investigated 37 consumer products and developed a design repository considering materials and manufacturing data, CAD models, and 22 environmental impact indicators. They applied three different LCA methods to evaluate the environmental impacts of design decisions on consumer products, i.e., manual calculation of impacts (based on Eco-Indicator 99), GaBi software (ReCiPe 2008), and SolidWorks Sustainability software. Their approach can assist in sustainable design decision making by identifying the product attributes with the largest environmental impacts. However, the approach requires users to be familiar with product lifecycle impacts. The limitations of the foregoing studies highlight the necessity for developing appropriate methods enabling decision makers the concepts of sustainable engineering.

2.3 Sustainability Assessment Methods and Software Tools

Globalization provided an opportunity for the manufacturers to make components of a product in different global locations and transfer them to one assembly location for completion into a final product to be delivered to consumers. While the early design phase cost account for only 5-7% of the entire product cost, 70-80% of the total product cost including material and resource consumption is determined in this phase [2]. A parallel situation could be hypothesized for the environmental impacts [1]. Moreover, this phase provides a significant opportunity for the designers to modify the product architecture to influence consumer behavior [1,46]. Thus, decisions at the early design phase have the highest impact on sustainability. To investigate sustainable product design, manufacturing activities at supply chain level and manufacturing level should be analyzed [3].

Some researchers have investigated supply chain network design during the early product design phase [18,94–96]. Chung et al. [97] investigated the life cycle consequences of modular design decisions. They developed a method, entitled the architecture and supply chain evaluation method (ASCEM) that considers the closed supply chain network as the assessment scope. The ASCEM applies the life cycle costs (LCC) and life cycle energy consumption (LCEC) enabling product designers to identify a product modular architecture with low life cycle costs and energy consumption in the early design phase. Chiu and Kremer [98] developed a graph theory based methodology to combine product and supply chain designs during the early design phase. The presented numerical programming formulation enables simultaneous optimization of product functions, manufacturing, and supply chain network configurations during the conceptual design phase.

Carbon footprint, often used as a sustainability indicator, is applied to measure environmental impacts and direct and indirect greenhouse gas (GHG) emissions from a specific activity [99]. Many researchers evaluated sustainability performance of supply chain networks considering carbon footprint [100–103]. The phase in the product life cycle that utilizes the most resources and causes the most environmental emissions is the manufacturing process – the main factor influencing the sustainability performance of an enterprise [104]. Designers and engineers need to quantify environmental impacts of new product designs and new manufacturing processes to achieve sustainable manufacturing [100]. Garretson et al. [59] defined sustainable manufacturing as *[t]he creation of goods or services using a system of processes that simultaneously addresses economic, environmental, and social aspects in an attempt to improve the positive or reduce the negative impacts of production by means of responsible and conscious actions.*

As shown in Figure 2, to assess environmental impacts of a product life cycle, the analyst needs to consider whether a production-oriented assessment (cradle-to-gate) or a product-oriented assessment (cradle-to-grave) should be conducted [105]. The majority of product-related GHG emissions are often produced within the cradle-to-gate scope, which offers companies prime opportunities to reduce carbon footprint and meet other business objectives [106]. Gao et al. [107], [108] developed a spreadsheet model to analyze how a manufacturing process plan influences product cost and environment. They used a bottom-up process-based method to estimate manufacturing costs for different production volumes. For quantifying environmental impacts, a process-based life cycle assessment in a cradle-to-gate scope was utilized.

Eastwood and Haapala [63] combined unit manufacturing (UMP) process modeling and life cycle inventory (LCI) techniques to develop a cradle-to-gate product sustainability assessment methodology. The methodology can improve the accuracy of existing approaches for measuring all three pillars of sustainability during the design for manufacturing processes, while also supporting manufacturing decision makers. Alsaffar et al. [44] developed a methodology and a framework to evaluate the environmental and social performance of product, process, and supply chain network configurations. They utilized process-based parametric modeling in a cradle-to-gate scope to simultaneously characterize UMPs and supply chain network designs. They applied the framework to the production of bicycle pedal components, which required a priori knowledge of the product, process, and supply chain design and characteristics. These methods have been largely developed for expert-users [109], which limits their usefulness in engineering education.

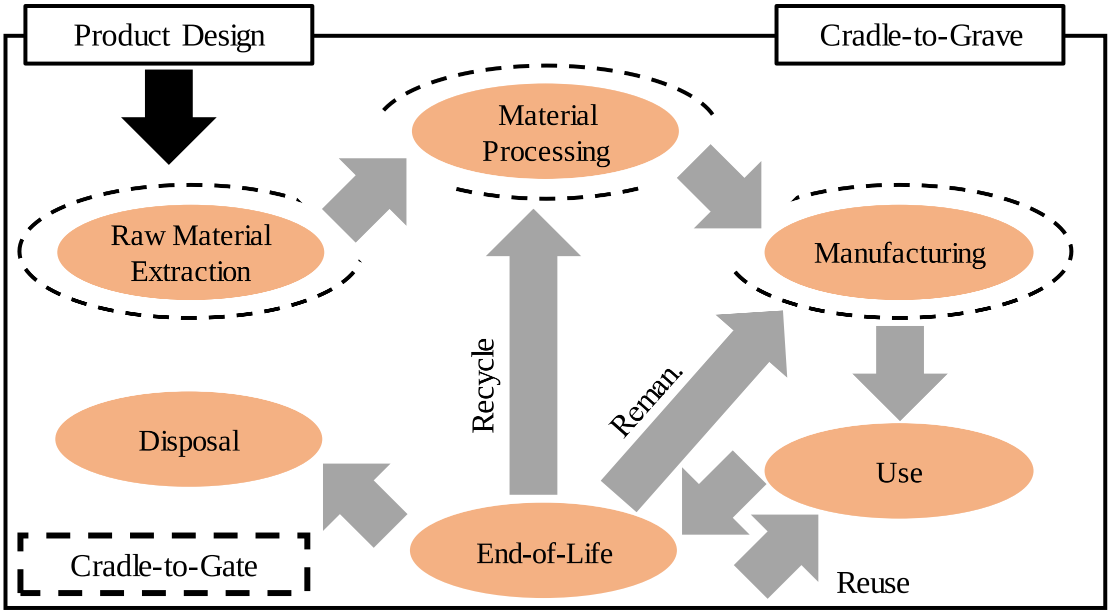


Figure 2. Product life cycle (adapted from Haapala et al. [105])

2.4 Limitations of Prior Work

Prior research has investigated process-based methods decision makers can use to evaluate the cradle-to-gate product life cycle scope from a sustainability perspective. In addition to these methods, several life cycle assessment (LCA) software tools have been developed to quantify the environmental impacts of the products. GaBi [10] and SimaPro [9] are the most commonly used tools to conduct LCA. OpenLCA [7], an open source LCA tool, is another tool that has gained attention from researchers. Moreover, many simplified LCA tools such as, Sustainable Minds [6] and Quantis Suite 2.0 [110] have been developed; this batch considers simplifications at levels of data input, user interface, and calculation methods, etc. Another category of the LCA tools is CAD-integrated systems to evaluate the sustainability performance of the product design. In addition to eco-design tools, such as, EcoFit [11], EcoCAD [12], and EcologiCAD [13], that are recently developed to enhance designers' capability to assess the environmental impacts during the design phase, commercial tools such as, SolidWorks Sustainability [5] have been designed to quantify environmental impacts using the CAD model of an intended product.

Rossi et al. [14] reviewed eco-design methods and tools over the past twenty years to identify the main barriers that restrict their effective use in industrial companies. They found that LCA tools need an expert for their use. One other challenge of these LCA tools is the high level of detailed information to quantify the environmental impacts of the product [1]. Although simplified LCA tools are more user friendly, their users still need training to apply them. Moreover, over-simplification causes interpretation reliability issues. Regarding the CAD-integrated tools, two challenges have been identified explaining their limited industrial adoption [111]. First, tools are too qualitative or subjective for designers with limited experience; and second, they are time-consuming, expensive, and not well-integrated with other tools used during the early design phases. In today's world, it is important to work in a collaborative environment [112] to enhance the concurrent design activity. Simplifications in product modeling often lessen the much needed details in results [14]. Finally, LCA tools, in general, relate the impacts of manufacturing processes and supply chain directly to the product mass. Thus, the impact of design changes that keep the product mass and/or process parameters unchanged cannot be investigated [38,113].

2.5 Contributions of this Research

The focus areas of the existing literature described in the prior sections are summarized in Table 3. The leftmost column presents whether a framework was developed in the reviewed paper. The next column presents the product life cycle scope investigated in each paper. The next two columns indicate the type of design repository information included in each paper. Next, the table reports the sustainability characterization methodology used. In the next two columns, the objectives of the papers are identified, which show if they concentrated on optimizing or evaluating the product design in terms of sustainability performance measures. The ease of use, presented in the next two columns, indicates whether the method and software tool developed in each paper is accessible and whether a design repository is developed. The next three columns present the sustainability aspects investigated. Finally, the last two columns describe whether the manufacturing information included in each paper is experimental or modeled.

As evidenced from the foregoing, a framework is needed that will enable non-expert decision makers to investigate the concepts of sustainability assessment by quantifying the impacts of product design changes on manufacturing processes during early product design. An integrated sustainability assessment framework to address the gaps identified in the literature is described in Chapter 3. In addition, in order to demonstrate this sustainability assessment framework, a proof-of-concept software tool is developed and implemented, as described in Chapter 4. Finally, to evaluate the operational performance of the tool, a user study was designed and undertaken, as discussed in Chapter 5.

Table 3. Summary of the literature review

Framework development	Life cycle stage(s) considered	Input of design information		Process characterization		Objective of the analysis		Ease of use of the method		Sustainability aspect(s) evaluated			Manufacturing information obtained by		Source(s)
		CAD-integrated	User entry of data	UMP model	LCA tool data	Optimization	Evaluation	Accessibility of the tool	Repository available	Environmental	Economic	Social	Experiment	Modeling	
✓	Product design	✓					✓	online	✓			✓			[88,114]
	Cradle-to-gate		✓		✓		✓	online	✓	✓			✓		[91,115]
	Cradle-to-gate	✓		✓			✓		✓	✓				✓	[92,116,117]
	Cradle-to-grave		✓		✓	✓		online	✓	✓			✓		[93]
	Cradle-to-gate		✓		✓		✓		✓	✓			✓		[89,90,118]
✓	Cradle-to-gate			✓			✓			✓				✓	[26]
	Cradle-to-gate		✓	✓			✓			✓				✓	[38]
✓	Cradle-to-gate		✓	✓			✓	online		✓	✓			✓	[45]
*	Cradle-to-gate		*	*			*	online	*	*	*	*		*	-

* The contribution of the research presented herein

Chapter 3: A FRAMEWORK FOR INTEGRATED DESIGN AND MANUFACTURING SUSTAINABILITY ASSESSMENT

To achieve the objective of this research, a framework is developed herein to facilitate simultaneous analysis of economic, environmental, and social impacts of product design changes across manufacturing processes and supply chain networks by decision makers, including non-experts in sustainability assessment. The framework developed (Figure 3) considers a cradle-to-gate life cycle scope and has four phases: (1) product development, (2) supply chain configuration, (3) manufacturing process design, and (4) manufacturing process and system (MaPS) sustainability analysis. The first phase of the framework applies a product development approach and provides product design information (e.g., geometry and material) for the next phases. In the second phase, supply chain configuration approach has been applied to create the supply chain, which includes supplier selection and determination of transportation modes and routes.

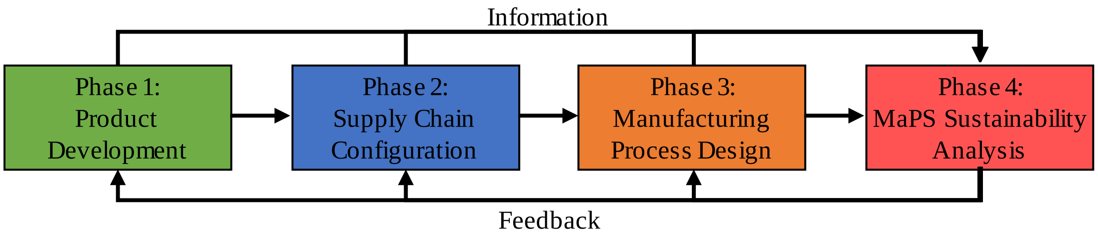


Figure 3. Framework for sustainable product design and manufacturing analysis

In the third phase, to provide detailed manufacturing information (e.g., the UMPs required to make the product and their associated process parameters), manufacturing process design approach is utilized. Finally, in the fourth phase, manufacturing process and system sustainability assessment is conducted using the information provided in the previous phases to quantify the environmental, economic, and social impacts.

The framework developed herein is presented in greater detail in Figure 4. Each phase includes a set of activities (or steps), which are developed based on prior work. Each phase of the framework is described in more detail in Sections 3.1-3.4.

3.1 Phase 1: Product Development

As presented above in Figure 2 (Section 2.3), the product life cycle originates from a product design. Thus, the first phase of the framework developed herein focuses on providing the product design information, such as materials, components, functions, and geometry, based on the product development approaches summarized in Table 4.

Table 4. Summary of product design/development approaches

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Source
Identify need	Plan for the design process	Develop engineering specifications	Develop concepts	Develop product	-	-	[2]
Clarify objectives	Establish functions	Set requirements	Determine characteristics	Generate alternatives	Evaluate alternatives	Improve Details	[119]
Concept development	System-level design	Detail design	Testing and refinement	Production ramp-up	-	-	[120]
Analyze the situation	Formulate search strategies	Find product ideas	Select product ideas	Define products	Clarify and elaborate	-	[121]

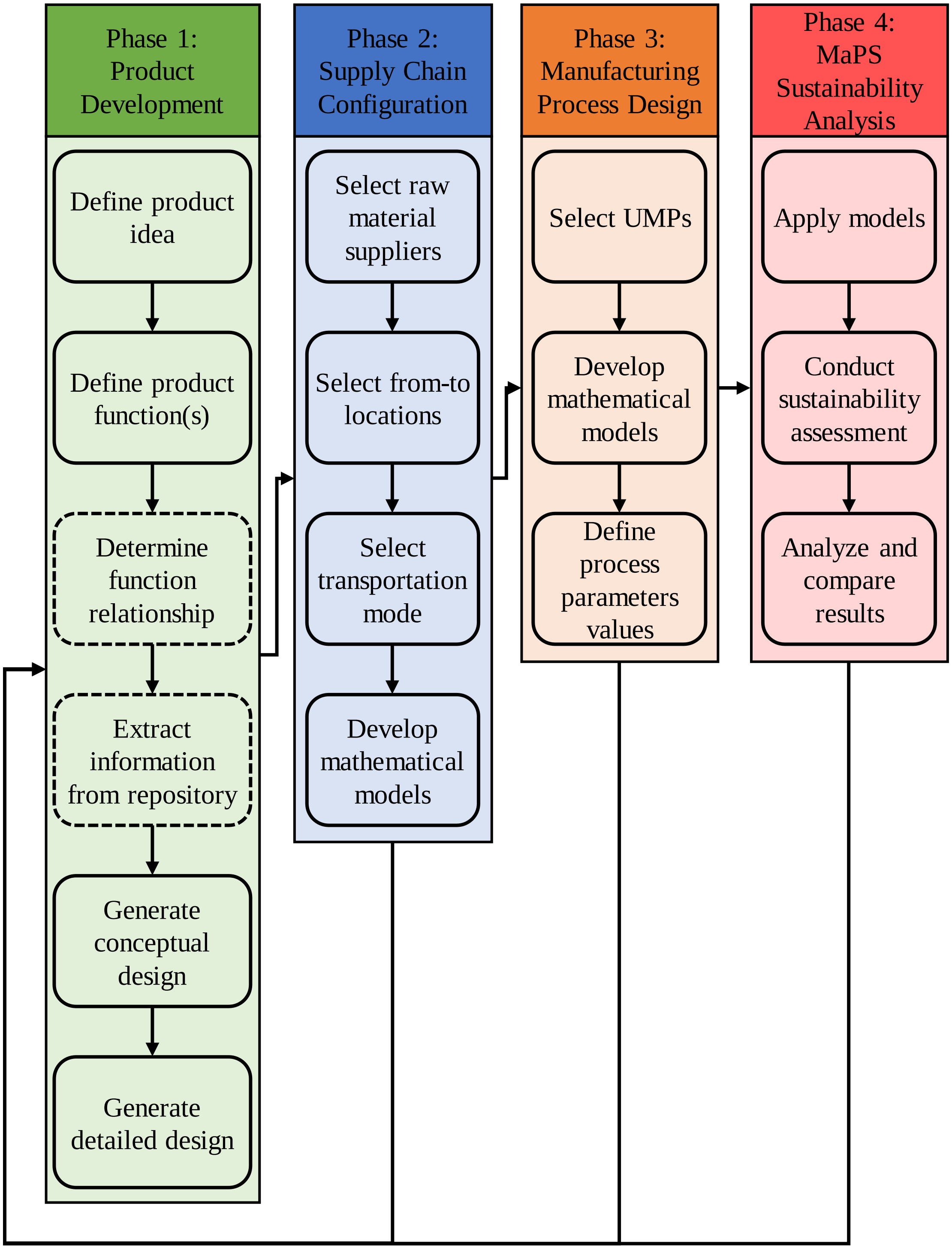


Figure 4. Activities comprising each phase of the framework to facilitate sustainable product design and manufacturing analysis

As presented in Table 4, the typical major steps in product development are to: (1) define the product idea, (2) define product function(s), (3) generate product conceptual design, and (4) generate product detail design. Thus, the product development phase developed herein follows these major steps and starts with defining the product idea, which includes exploring new and innovative products as well as redesigning existing products. This step is founded upon market trends and needs (e.g., popular products such as multicopters and fidget spinners) or a client specific demand (e.g., one-handed household water mixing tap). Next, product functions, such as lifting power of a multicopter or capacity of a container, should be defined to meet market goals and customer requirements.

The next two activities often followed in product development, which are indicated with dashed boxes in Figure 4, are pursued for the new and innovative products. The first would determine product functionality relationships based on key design specifications (e.g., needed rotor disk area based on the desired multicopter lifting power). Although a design repository is not always required to design a product, it can assist decision makers by providing them with initial alternatives while designing their intended product. The designer would then have the opportunity to identify the components that suitably meet the product functional requirements. The next step is to generate the product conceptual design based on the product functionality and the information captured from the repository. The last step is to generate the detailed product design by defining the materials to be used and the dimensions of components.

3.2 Phase 2: Supply Chain Configuration

One of the key pieces of information provided in the first phase of the framework is the raw material used in making the intended product. Given the product life cycle scope considered in the framework, a supply chain network should be created to deliver the raw material from supplier to manufacturer. To do this, the second phase of the framework applies a supply chain configuration approach [18,122–126]. Since the first two activities of the cradle-to-gate life cycle scope (i.e., raw material extraction and processing) happen at the supplier facilities, selecting raw material suppliers is the first step in this phase. Supplier selection is important in the supply chain network design, since the environmental (e.g., energy consumption and the resulting carbon footprint), economic (e.g., lead time and cost), and social (e.g., worker health and safety) impacts vary in different locations [127].

After completion of raw material processing, the intermediate material needs to be transported to manufacturing facilities as presented in Figure 2. In the second step, two types of destinations are considered in the framework: connecting and manufacturing. While manufacturing destinations implement manufacturing processes, connecting destinations are locations at which material intermediate forms are delivered to the manufacturer without any extra activity or processing. After determining the transportation routes in step two, transportation modes should be selected in the third step. The last step of this phase focuses on developing numerical equations to quantify the selected sustainability metrics. In addition to the design information, the equations need supply chain data, such as distances and transportation capacity.

3.3 Phase 3: Manufacturing Process Design

As presented in Figure 2, the after creating the supply chain network, manufacturing is the next phase in the cradle-to-gate life cycle scope. This phase of the framework provides detailed manufacturing information through unit manufacturing process (UMP) modeling to be used in the last phase of the framework. Each manufacturing process flow is composed of several UMPs. To identify, evaluate, and select a sequence of UMPs for fabricating the product, a manufacturing process design (MPD) approach is applied herein [128]. MPD involves UMP selection based on the product design specification (e.g., raw material and geometry), process requirements, and production quantity per year. Moreover, it investigates the physics and the chemistry of the capital equipment, shaping tools, and work holding tools for the UMPs required for making the product to generate the related costs in a bottom-up manner.

After selecting the required UMPs, numerical models should be developed for each of them. Developing the UMP models is the most time-intensive step in the framework as it involves gathering data and developing transformation equation for each of the metrics selected to quantify the sustainability performance. It is not expected that non-experts would accomplish this step by themselves. Thus, as a critical part for conducting sustainability assessment in this framework, UMP models should be provided for non-experts. The numerical models of the UMPs should describe the outputs (values for the selected sustainability metrics) as a function of inputs (design and process specific parameters). Finally, the process parameters are defined at the last step of the manufacturing process design phase.

3.4 Phase 4: Manufacturing Process and System Sustainability Analysis

Once the product design, supply chain, and manufacturing information are provided through Phases 1-3, the framework proceeds to the last phase, which is manufacturing process and system (MaPS) sustainability analysis. This phase aims to implement sustainability assessment and has three activities. In the first step, numerical models for the supply chain activities and the UMPs determined are applied to perform metric quantification. Next, based on the modeling results, an assessment of the sustainability metrics can be conducted to identify "red flags" (potential no-go issues) and "hot spots" (potential areas of improvement) in the product cradle-to-gate life cycle. In this manner, decision makers will be able to investigate the impacts of suppliers from different locations, transportation modes and routes, and manufacturing processes on the sustainability performance.

Finally, after iterating on design alternatives, decision makers will need to compare assessment results to identify the best alternative. In addition, they can use the new information to investigate other ways to improve the sustainability performance. They can change the product design specifications, such as the materials and geometry, or design a new product and accordingly, create a new supply chain network and select different manufacturing processes for making the product. This enables decision makers, including non-experts, to promote sustainable product design by investigating the impacts of product design changes on supply chain networks and manufacturing processes from sustainability perspective.

As mentioned above, one of the main challenges for the non-experts to conduct UMP-based sustainability assessment from cradle-to-gate life cycle scope is developing the numerical models for the supply chain activities and the manufacturing processes. Moreover, gathering the data (e.g., distances, process parameters) for each activity within the framework is another challenge. Thus, as identified in Chapter 2, to enable non-experts to conduct sustainability assessment using UMP modeling approach, a software tool is required. The tool needs to be user-friendly and needs to include the numerical models and the required data to conduct sustainability assessment. An application of the framework and a proof-of-concept tool developed in this work to conduct UMP-based sustainability assessment are demonstrated in Chapter 4.

Chapter 4: DEMONSTRATION OF THE FRAMEWORK

A proof-of-concept tool, termed the Manufacturing Process and System (MaPS) Sustainability Analysis Tool is developed to aid the implementation of sustainability assessment using standards-based unit manufacturing process models. The tool is publicly available [50], and addresses the identified deficiencies of sustainability assessment through an integrated framework for product, supply chain, and process design, and demonstrates the application of the developed framework for supporting non-expert designers and decision makers. Elements of this tool are derived from work under a collaborative research project entitled *Constructionism in Learning: Sustainable Life Cycle Engineering (CooL:SLiCE)* [45], supported by the U.S. National Science Foundation at Iowa State University, Oregon State University, Pennsylvania State University, and Wayne State University. The four universities worked collaboratively to provide an innovative, distributed cyberlearning platform for students to analyze the effect of changes to product designs, manufacturing processes, and supply chain configurations on sustainability performance [45]. The work at Oregon State University focused on manufacturing process modeling.

The tool was designed to align with the four phases of the integrated sustainability assessment framework (Chapter 3), and support the investigation of environmental impacts across the cradle-to-gate life cycle. In addition, the tool can be used to evaluate economic and social performance by quantifying the cost of goods sold and the safety in the work environment, respectively. The tool is composed of four modules that map to each phase of the sustainability assessment framework as presented in Figure 5.

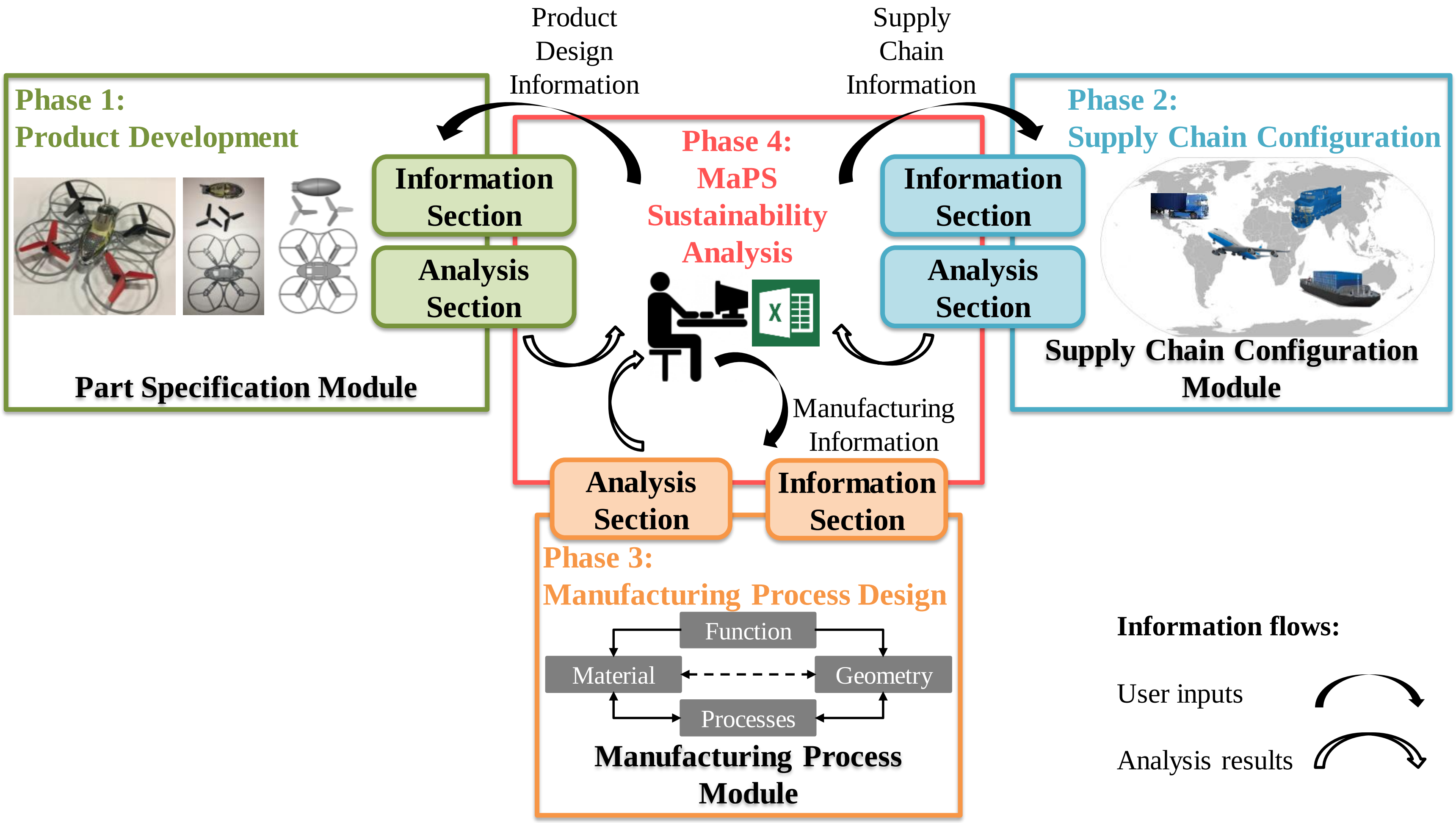
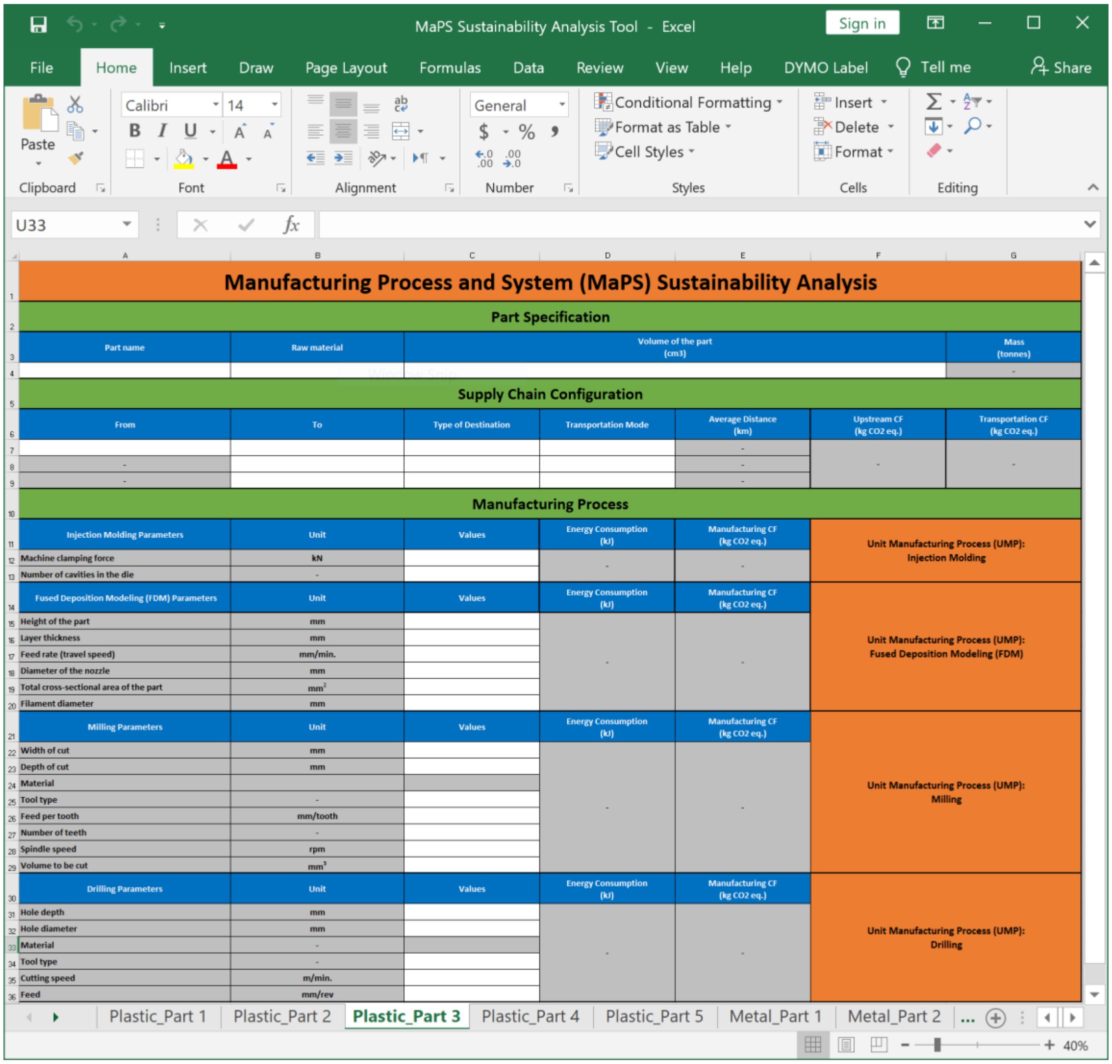


Figure 5. Mapping of MaPS Sustainability Analysis Tool modules with sustainability assesement framework phases

To realize Phase 1 (Product Development) of the framework, the part specification module captures product design information (e.g., materials and product geometry). Similarly, supply chain information (e.g., transportation routes and modes) is provided by the Supply Chain Configuration module, which maps to Phase 2 (Supply Chain Configuration). In addition, the manufacturing process module provides manufacturing information (key process parameters and their associated values in each UMP), realizing Phase 3 (Manufacturing Process Design) of the framework.

Each of the four tool modules has two sections: *information* and *analysis*. While each module performs the sustainability assessment independently through its associated *analysis* section, the *information* sections of the modules share the required information for conducting the sustainability assessment. Numerical models for each activity are implemented as spreadsheet models (MS Excel) in the *information* section of each module. The *analysis* sections of the modules are integrated in a graphical user interface (Figure 6) for easier access and data entry by non-experts.

This remainder of this chapter is organized with respect to the four phases of the integrated sustainability assessment framework defined in Chapter 3. The activities (steps) comprising each phase are described and demonstrated using a case study for the sustainable design of a hexacopter. Moreover, for each phase, the application of the associated MaPS Sustainability Analysis Tool modules is presented.



Manufacturing Process and System (MaPS) Sustainability Analysis

Part Specification

Part name	Raw material	Volume of the part (cm3)	Mass (tonnes)
			-

Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		

Manufacturing Process

Injection Molding Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Machine clamping force	kN		-	-	Unit Manufacturing Process (UMP): Injection Molding
Number of cavities in the die	-				
Fused Deposition Modeling (FDM) Parameters	**Unit**	**Values**	**Energy Consumption (kJ)**	**Manufacturing CF (kg CO2 eq.)**	
Height of the part	mm		-	-	Unit Manufacturing Process (UMP): Fused Deposition Modeling (FDM)
Layer thickness	mm				
Feed rate (travel speed)	mm/min.				
Diameter of the nozzle	mm				
Total cross-sectional area of the part	mm^2				
Filament diameter	mm				
Milling Parameters	**Unit**	**Values**	**Energy Consumption (kJ)**	**Manufacturing CF (kg CO2 eq.)**	
Width of cut	mm		-	-	Unit Manufacturing Process (UMP): Milling
Depth of cut	mm				
Material					
Tool type	-				
Feed per tooth	mm/tooth				
Number of teeth	-				
Spindle speed	rpm				
Volume to be cut	mm^3				
Drilling Parameters	**Unit**	**Values**	**Energy Consumption (kJ)**	**Manufacturing CF (kg CO2 eq.)**	
Hole depth	mm		-	-	Unit Manufacturing Process (UMP): Drilling
Hole diameter	mm				
Material	-				
Tool type	-				
Cutting speed	m/min.				
Feed	mm/rev				

Figure 6. MaPS Sustainability Analysis Tool graphical user interface

4.1 Phase 1: Product Development

The first phase of the integrated sustainability assessment framework focuses on product development. The activities of this phase are presented in Figure 7.

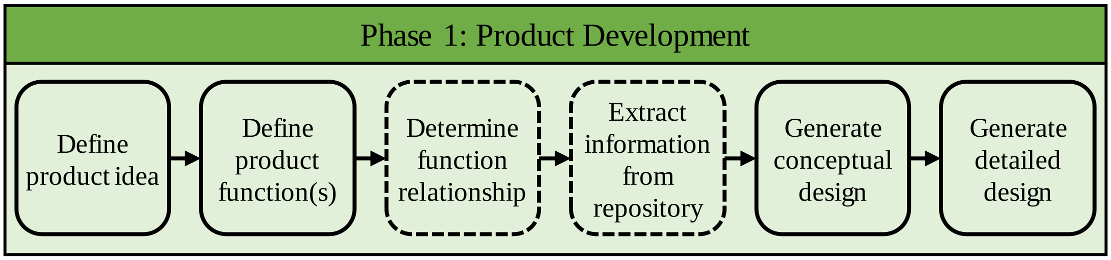


Figure 7. Activities under Phase 1 of the sustainability assessment framework

Multicopters have become popular, and it is expected that students from different regions, backgrounds, and genders would be interested in learning more about this technology as well as becoming more familiar with personalized, sustainable design of multicopters and other products through material, shape, and size modification. By considering the market opportunities, a multicopter for package delivery is defined as the **product idea**. In the second step, we define lifting power as the **product functionality** in focus for multicopter redesign. The ensuing sustainable design activity will consider the product design, supply chain, and manufacturing elements that impact cost, environmental impact, and worker safety.

The next step is to **determine the functionality relationship** based on key design specifications. In this example, we define the relationship as the rotor disk area (RDA), since lifting power is the product functionality in focus. RDA, as presented in eq. 1, is a function of the number of motor axes (N_a), number of blades per propeller (N_b), and the blade length (L_b).

$$\mathrm{RDA} = \pi \times \left(\frac{N_a \times N_b \times L_b}{2}\right)^2 \tag{1}$$

Next, in considering sustainability performance while meeting the lifting power needs, the effect of product design changes on manufacturing processes will be considered by evaluating two **conceptual design** scenarios: (1) The same types of multicopters with a different number of blades per propeller and (2) Different types of multicopters with the same number of blades per propeller. Defining the conceptual designs and detailed design information is aided by developing a **design repository**, as described below. It should be noted that multicopters can be classified based on the number of motor axes and their leg orientation. Table 5 presents the taxonomy developed under this research for classifying different multicopters. Shape-type (e.g., “Y-shaped tri-copter” or “x-shaped quad-copter”) is utilized for naming the multicopters. Two-axis copters are named based on their shape while the five- and 10/+10-axis multicopters are named based on their type. A +-shaped copter has its legs set at 90° angles, while the legs of an x-shaped copter are at an angle other than 90°.

Table 5. Taxonomy of multicopters

No. of axes	Type	Shape					
		x	+	Y	H	V	Other
2	Bicopter						Dual, Twin
3	Tricopter			✓			T-shape
4	Quadcopter	✓	✓	✓	✓	✓	
5	Pentacopter						5-axis
6	Hexacopter	✓	✓	✓	✓		
8	Octocopter	✓	✓				X8-shape
10/+10	10/+10 axis						10/+10-shape

The differences in multicopter shapes is presumed to have a small effect on lifting power, so only the x-shape is considered in this case. A combination of the two scenarios was applied and two conceptual product designs (PD1 and PD2) were developed by altering N_a and N_b, as presented in Table 6. As PD2 has more axes than PD1, it is posited that increasing the number of axes will ultimately increase the environmental impacts during manufacturing.

Table 6. Product design configuration

Product design (PD)	No. of axes	No. of blades per propeller	Type	Shape
PD1	4	2	Quadcopter	x-shape
PD2	6	3	Hexacopter	x-shape

With the design concepts specified, detailed design specifications must be determined. The required RDA (i.e., blade length and number of blades) must be calculated to meet the design functionality (lifting power defined by payload mass lifted). However, such an activity can be challenging and time-consuming for designers. Thus, several x-shaped quadcopters and hexacopters, as well as a dual copter, were purchased. Further, solid models were created (Figure 8) to capture design information and testing was performed to measure lifting power. This information was used to populate a simple design repository, as well as defining functionality relationships.

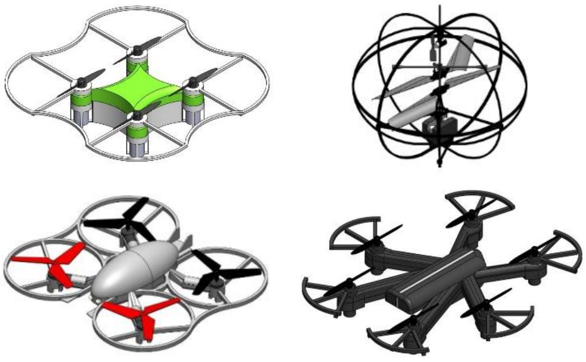


Figure 8. Multicopters purchased for this study

The repository includes the CAD model and information about the maximum mass lifted (payload), dimensions, and product mass (Table 7). The product mass is comprised of body mass (typically upper and lower shells, battery cover, fasteners, and auxiliary components) and the electronics mass (battery, motors, wires, and printed circuit board (PCB)).

Table 7. Summary of design repository information for selected multicopters

No.	Max Payload (g)	No. of axes	No. of blades per propeller	Rotor disk area (cm^2)	Blade dim. (mm)		Multicopter mass (g)	Electronics mass (g)		
					Length	Width		Battery	Motor	Wires and PCB
1	9	4	2	127	15.9	4.3	15	3	8	4
2	10	6	2	254	15.0	4.5	21	5	10	5
3	22	4	3	1018	30.0	8.0	34	10	13	7
4	34	2	2	745	77.0	18.2	50	17	8	6
5	64	6	2	855	27.5	7.9	72	22	28	6
6	98	4	2	2307	67.8	17.7	131	70	34	15

To measure the lifting power (maximum mass lifted), the battery of each multicopter was fully charged in each flying experiment to assure peak performance. After flight testing, each multicopter was disassembled to measure and record the part dimensions and masses. Finally, CAD models of each part and the assembled multicopter were developed. These activities are displayed in Figure 9.

Figure 9. Testing with various weights (left), disassembled quadcopter (middle), and CAD models (right)

Based on measured maximum payload masses for the multicopters, a graph (Figure 10A) was created to illustrate the numerical relationship between mass lifted and RDA. This graph enables designers to identify the required RDA of their design by considering the intended payload mass. They are then able to calculate the necessary blade length by using eq. 1. To further assist the designer, the graph shown in Figure 10B illustrates the relationship between typical blade length and width, and consequently, allows novice designers to define the needed blade dimensions.

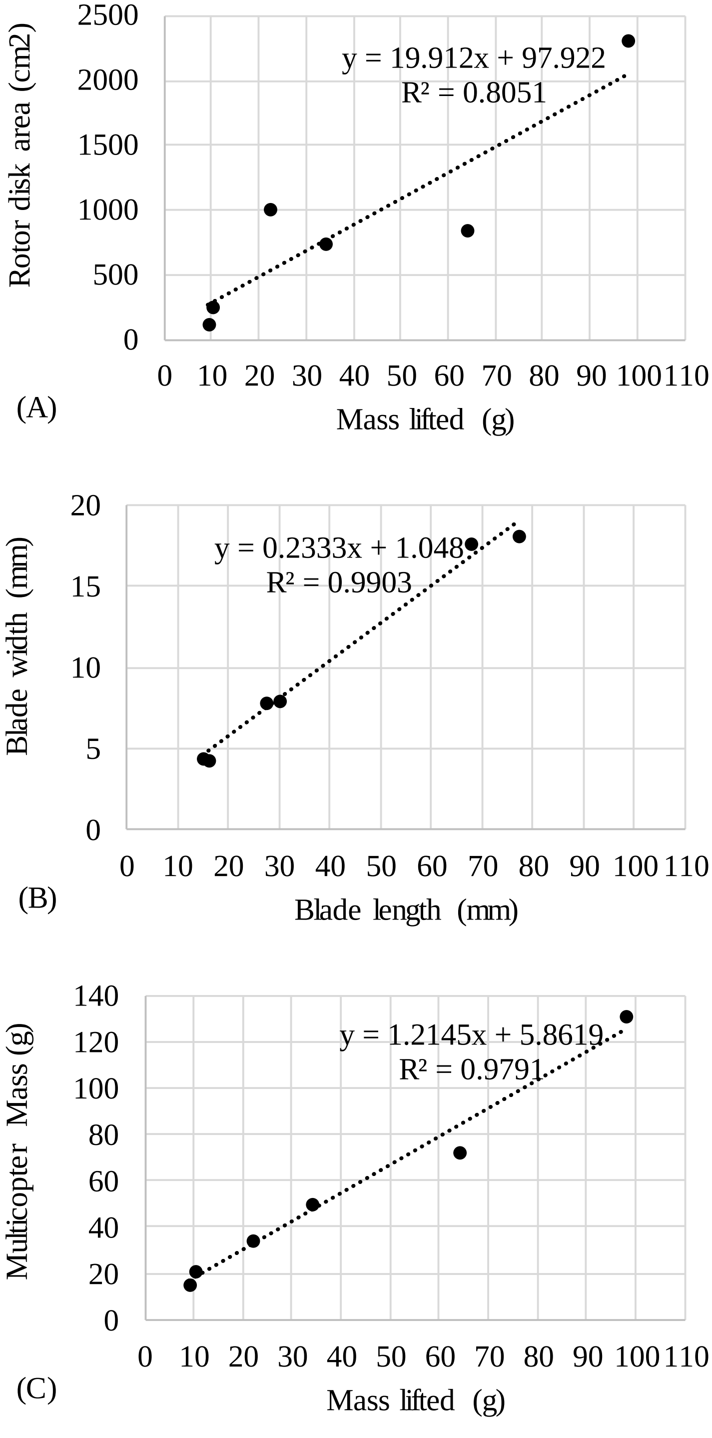


Figure 10. Relations of (A) mass lifted and rotor disk area, (B) blade length and blade width, and (C) mass lifted and mass of the multicopter

Equation 2 can be used to calculate the propeller mass, M_P, based on the blade volume and density of the material.

$$M_P = (V_b \times \rho \times N_b) \times N_a \tag{2}$$

Based on our observations during the disassembly of multiple multicopters during repository development, we assume blade thickness is 1.0 mm in this case study. Although there are variations in the shapes of the propellers, we further assume all propellers have an oval shape. From Figure 10, it can be seen that blade dimensions are highly consistent (R^2=99%), and the relationship between RDA and mass lifted is fairly consistent (R^2=80%), allowing for a meaningful propeller design experience. Further, as shown in Figure 10C, the total mass of materials contained in a range of multicopter designs correlates very well (R^2=98%) with lifting power, measured by payload mass.

In addition to the propellers, designers need to define the multicopter body structure. Based on the multicopters obtained to develop the design repository, two main body structures were identified. The first structure has an upper shell, lower shell, and individual legs, while in the second structure, the upper and lower shells also comprise the legs and house the electrical components. To avoid confusion, we assume all the multicopters follow the first body structure. To enable calculation of the mass of the multicopter electrical components, Figure 11 was developed.

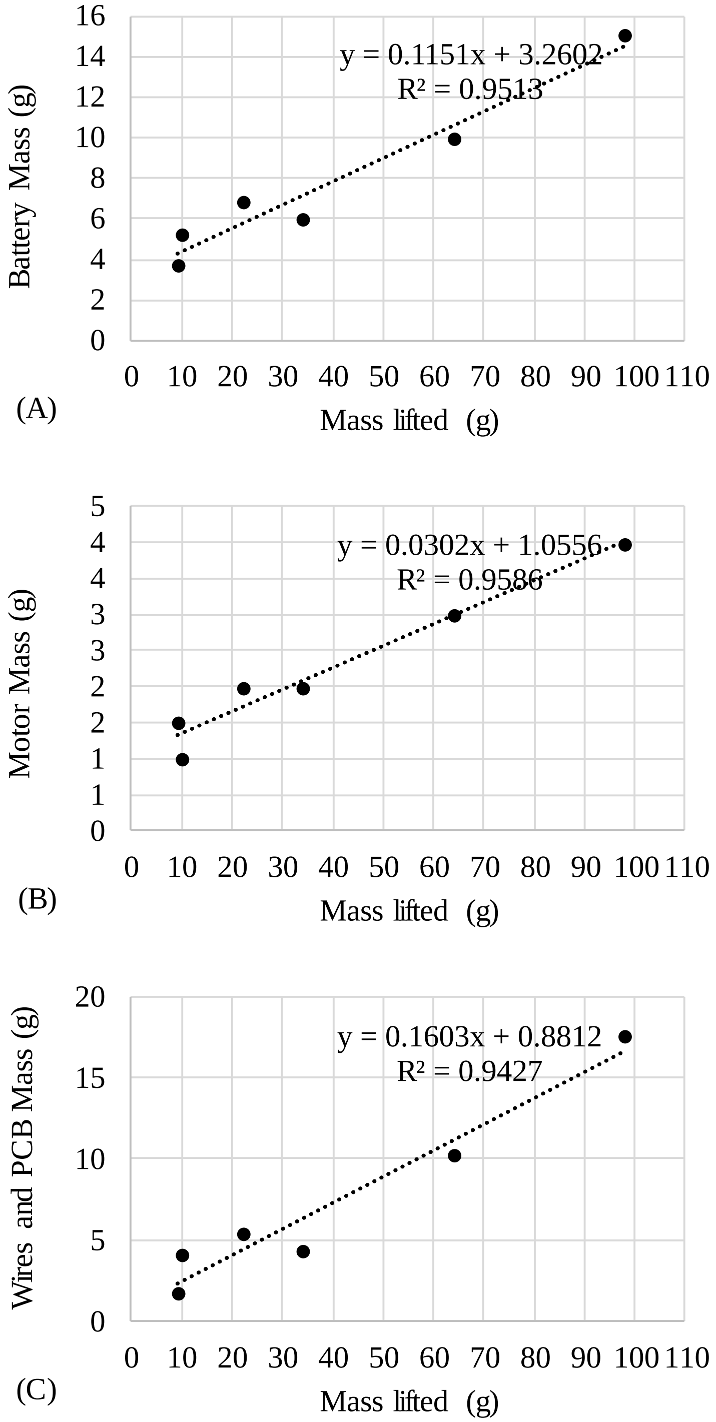


Figure 11. Relation between mass lifted and mass of the (A) battery, (B) motor, and (C) wires and PCB

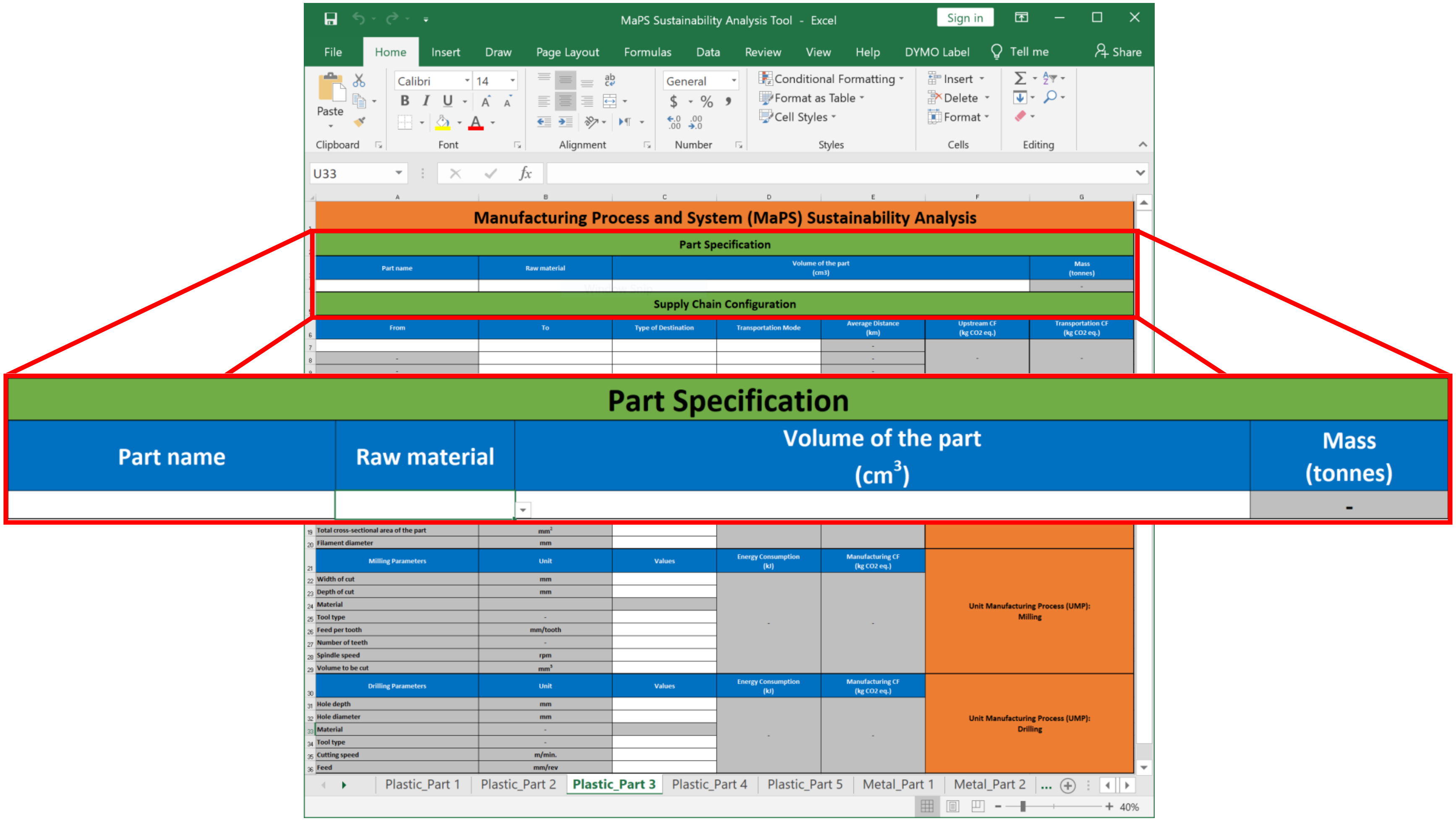
The difference between the total mass of the multicopter and the mass of the propellers, battery, and electronics provides the mass of the body. The figure presents the relationships between the mass lifted and the mass of the multicopter (Figure 11A), battery (Figure 11B), and electronics (Figure 11C). Again, the relationships are found to be quite consistent, based on their R^2 values (94.3%-95.9%).

Based on repository information, two hexacopters for delivering letters (60 g maximum payload) are designed. The RDA is found to be 1290 cm^2, and blade length is calculated using eq. 1 for each product design by considering the specific number of axes and blades per propeller (Table 6). To extend useful life, propellers will be made from stainless steel using powder metallurgy. The mass of the polymer hexacopter, battery, and electronics are determined from Figure 11, as summarized in Table 8.

Table 8. Summary of the product design specifications for the two multicopters

No.	No. of axes	No. of blades per propeller	Blade length (cm)	Blade width (cm)	Blade volume (cm^3)	Shell mass (g)
PD1	4	2	5.07	2.23	7.58	46.29
PD2	6	3	2.25	1.57	3.77	40.65

This information is input to Part Specification module of the MaPS Sustainability Analysis Tool using drop-down menus. The information is processed by the *analysis* section of the module to provide feedback to the user as well as the *information* sections in the other modules for further processing. A screenshot of the Part Specification module in the graphical user interface is presented in Figure 12.



Manufacturing Process and System (MaPS) Sustainability Analysis

Part Specification

Part name	Raw material	Volume of the part (cm3)	Mass (tonnes)
			-

Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		

Total cross-sectional area of the part	mm^2				
Filament diameter	mm				

Milling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Width of cut	mm		-	-	Unit Manufacturing Process (UMP): Milling
Depth of cut	mm				
Material					
Tool type	-				
Feed per tooth	mm/tooth				
Number of teeth	-				
Spindle speed	rpm				
Volume to be cut	mm^3				

Drilling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Hole depth	mm		-	-	Unit Manufacturing Process (UMP): Drilling
Hole diameter	mm				
Material	-				
Tool type	-				
Cutting speed	m/min.				
Feed	mm/rev				

Part Specification

Part name	Raw material	Volume of the part (cm^3)	Mass (tonnes)
			-

Figure 12. Part Specification module in the graphical user interface

4.2 Phase 2: Supply Chain Configuration

The second phase of the integrated sustainability assessment framework developed herein involves configuring the supply chain to deliver the raw material from the supplier to manufacturer. The activities of this phase are presented in Figure 13.

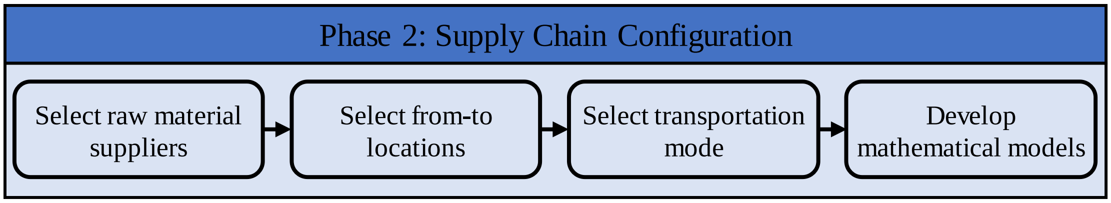


Figure 13. Activities under Phase 2 of the sustainability assessment framework

Representative supply chain configurations are created to produce each of the designs developed in Phase 1. Here, we **select raw material suppliers** and **select from-to locations** based on the required materials or process type and relevant common production locations. For making the propellers of the first product design (PD1), Beijing, China and San Francisco, CA, USA are considered as the production location for metal/polymer feedstock and the component manufacturing facility, respectively. Shanghai, China is assumed as the connecting city to transfer the raw materials from Beijing to San Francisco.

The supply chain configuration for making the shells in PD1 starts with making the plastic feedstock in London, UK. Then, the raw material is transported to New York, NY, USA as the connecting city. Manufacturing processes for making the shells occur in Houston, TX, USA. After making the propellers and the shells in their manufacturing facilities, they are transported to Chicago, IL, USA where assembly of the product occurs. The transportation routes and modes in the supply chains for producing the shells and propellers of PD1 are shown in Figure 14.

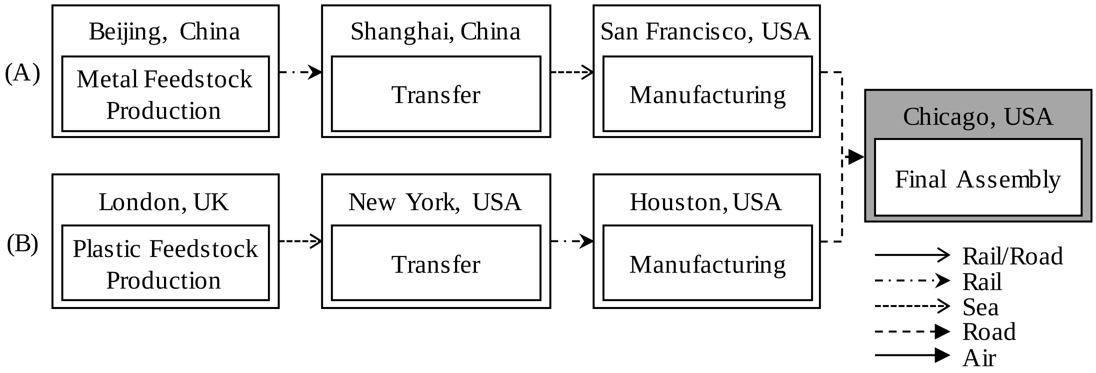


Figure 14. Supply chain configurations for manufacturing propellers (top) and shells (bottom) in PD1

In Figure 15, the transportation routes and modes in the supply chains for producing the shells and propellers of PD2 are presented. For making the propellers of the second product design (PD2), Montreal, Quebec, Canada and Riverside, CA, USA are considered as the production location for metal/polymer feedstock and the component manufacturing facility, respectively. Boston, MA, USA is assumed as the connecting city to transfer the raw material from Montreal to Riverside.

The supply chain configuration for making the shells in PD2 starts with making the plastic feedstock in New Delhi, India. Then, the raw material is transported to Austin, TX, USA as the connecting city. Manufacturing processes for making the shells occur in Anaheim, CA, USA. After making the components in their manufacturing facilities, they are transported to Irvine, CA, USA where assembly of the product occurs.

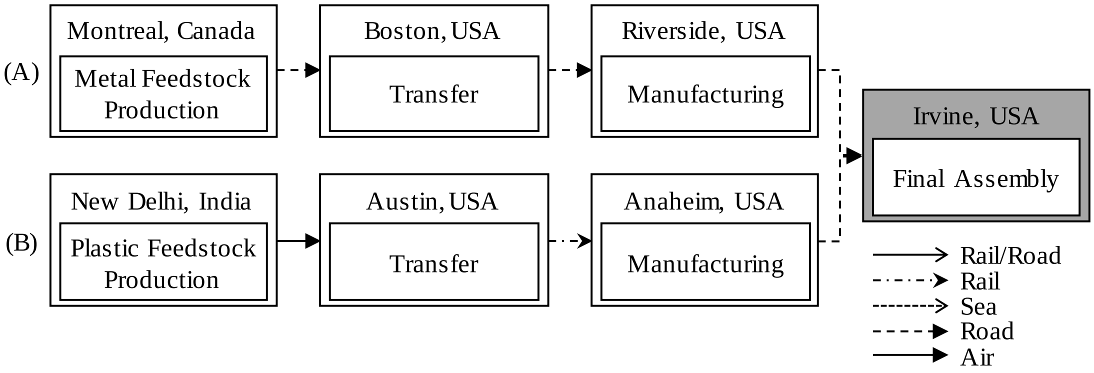


Figure 15. Supply chain configuration for manufacturing propellers (top) and shells (bottom) in PD2

The summary of the information for both supply chain configurations, describing the distances and the transportation routes and modes are presented in Table 9. All routes and distances were defined based on the distance calculators in Google Maps [129]. After capturing information about the product specifications and supply chain configurations, the next step is to define the manufacturing processes required to make the products. To do this, the manufacturing process design method is applied, as described in Section 4.3.

Next, two new indicators for the evaluation of worker safety are presented with respect to transportation processes. These indicators will supplement cost of goods sold and environmental impacts for a more comprehensive sustainability assessment.

Table 9. Supply chain configurations for production of PD1 and PD2

Design	Supply chain configuration	Transportation		
		From	To	Mode
PD1 (Propellers)	SC1A	Beijing, China	Shanghai, China	Rail
		Shanghai, China	San Francisco, US	Deep-sea container
		San Francisco, US	Chicago, US	Road
PD1 (Shells)	SC1B	London, UK	New York, US	Deep-sea container
		New York, US	Houston, US	Rail
		Houston, US	Chicago, US	Road
PD2 (Propellers)	SC2A	Montreal, Canada	Boston, US	Rail
		Boston, US	Riverside, US	Road
		Riverside, US	Irvine, US	Road
PD2 (Shells)	SC2B	New Delhi, India	Austin, US	Air freight
		Austin, US	Anaheim, US	Road
		Anaheim, US	Irvine, US	Road

Many metrics (e.g., child labor and level of community involvement) have been developed to quantify the social impacts of the activities within a supply chain [130,131]. Among these metrics, those such as quality of life, equity, and safety, which quantify the higher order needs instead of human basic needs are more favorable [132]. Thus, safety level in the work environment, whether within a factory or across the supply chain (including transportation activities), is investigated herein using nonfatal occupational injuries and illnesses (NOII) and days away from work (DAW) metrics. These two metrics are commonly understood and can be easily measured [63].

Moreover, they are directly related to time, which is an important factor that correlates with economic, environmental, and social impacts. Considering other social metrics, such as working hours, labor equity, and workload, would further emphasize the important role of time in sustainability analysis.

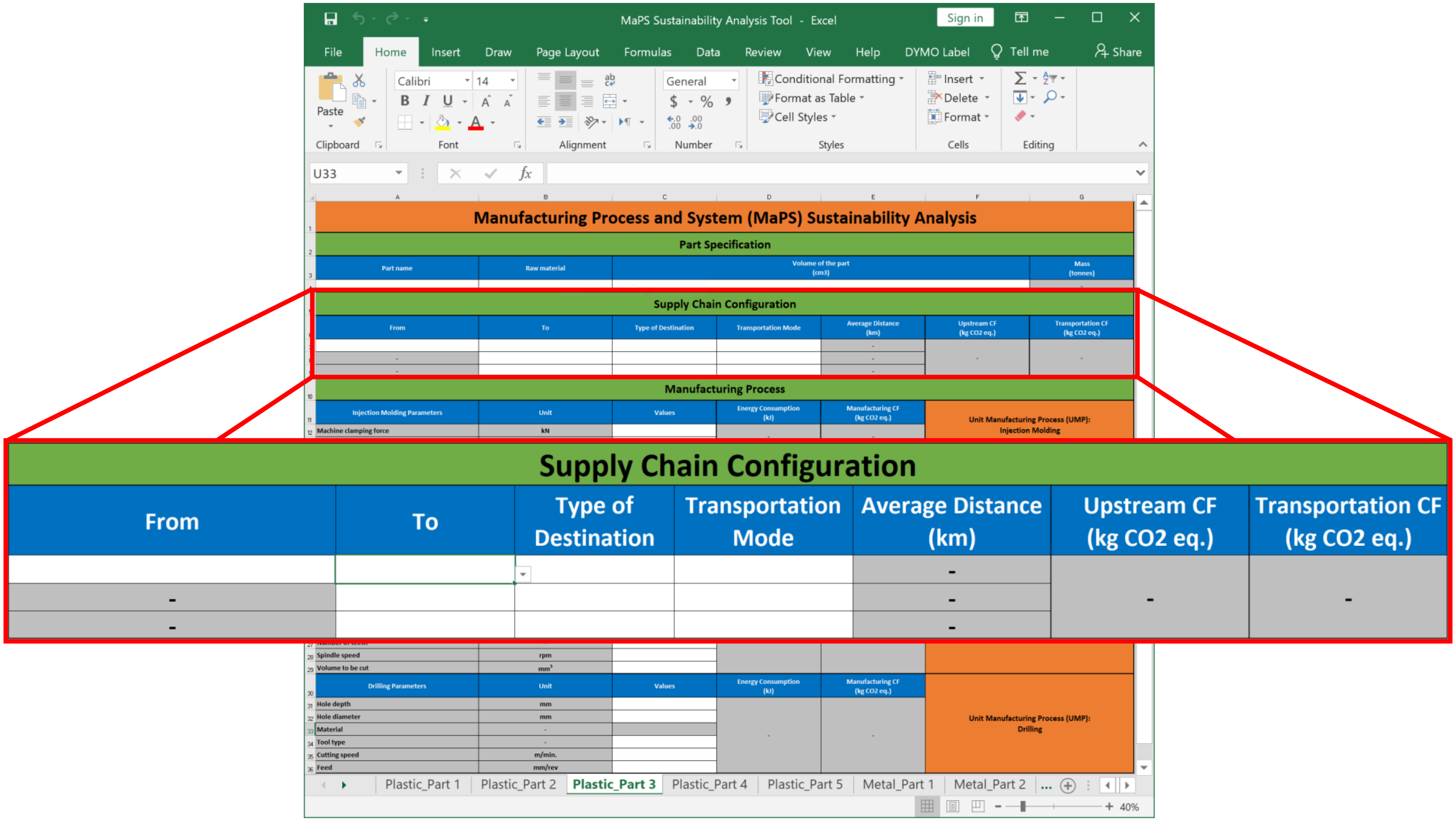
To quantify these two social metrics (i.e., NOII and DAW), data available from the supply chain or the U.S. Bureau of Labor Statistics (BLS) [133] can be utilized. To calculate nonfatal occupational injuries and illnesses for transportation activities ($\text{NOII}_{\text{trans}}$), transportation time is divided by the number of packaged products that could be transported using the indicated transportation mode to allocate the total number of injuries and illnesses impacts on a per-product basis. This ratio is multiplied by the annual production volume (PV) and the rate of nonfatal occupational injuries and illnesses ($\text{RNOII}_{\text{trans}}$) reported by the BLS for various transportation modes [133]. This value, as represented in eq. 3, is divided by 200,000 hours, which is assumed as the annual working hours for 100 equivalent full-time workers.

$$\text{NOII}_{\text{trans}} = \text{RNOII}_{\text{trans}} . \left(\frac{\left(\frac{t_{\text{trans}}}{N_{\text{trans}}} \right) . \text{PV}}{200000} \right) \tag{3}$$

To calculate DAW (eq. 4), the percentage of injuries and illnesses that result in days away from work must first be determined. The percentage is provided by dividing the rate of days away from work (RDAW) by the rate of nonfatal occupational injuries and illnesses (RNOII) for the relevant transportation mode from BLS data. This ratio is then multiplied by $\text{NOII}_{\text{trans}}$ to provide the total number of cases resulting in days away from work. Finally, this quantity is multiplied by the median days away from work (MDAW), from BLS data, to provide the total number of days away from work for each transportation activity.

$$\mathrm{DAW_{trans}} = \left(\frac{\mathrm{RDAW_{trans}}}{\mathrm{RNOII_{trans}}}\right).\mathrm{NOII_{trans}}.\mathrm{MDAW_{trans}} \qquad (4)$$

Similar to the Part Specification module, drop-down menus are provided for users to enter the supply chain information (transportation route and transportation mode) in the *information* section of the Supply Chain Configuration module. After capturing this information from the user, the *analysis* section provides distances, upstream carbon footprint, and transportation carbon footprint. Carbon footprint is a key environmental metric, which correlates with energy use [113] and is calculated as a part of Phase 4 activities under the Manufacturing Process and System Sustainability (MaPS) Analysis module. The MaPS Analysis module uses the part mass calculated by the Part Specification module to determine the mass of material/product transported. A screenshot of the Supply Chain Configuration module is presented in Figure 16.



Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		

Figure 16. Supply Chain Configuration module in the graphical user interface

4.3 Phase 3: Manufacturing Process Design

The third phase of the integrated sustainability assessment framework developed herein utilizes the manufacturing process design approach to identify, evaluate, and select a sequence of UMPs for fabricating the intended product. The three main activities of this phase are illustrated in Figure 17.

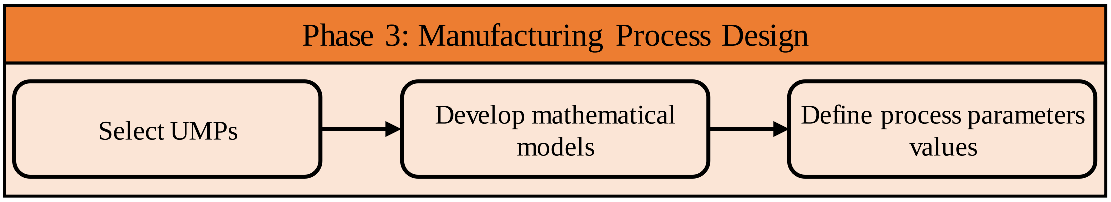


Figure 17. Activities under Phase 3 of the sustainability assessment framework

The proof-of-concept MaPS Sustainability Analysis Tool integrates several UMP models reported in the literature as well as a metal injection molding process model developed based on the UPLCI method. Using dropdown menus, non-experts would select appropriate values for each parameter (e.g., machining depth of cut or number of injection mold cavities) for each UMP required to make the product. The **UMPs are selected** based on the materials, geometries, and functions of the components to be produced Figure 18. The product functional requirements dictate the specifications for materials and part geometries. In turn, material and geometry specifications provide inputs used to select the required UMPs for making the intended product.

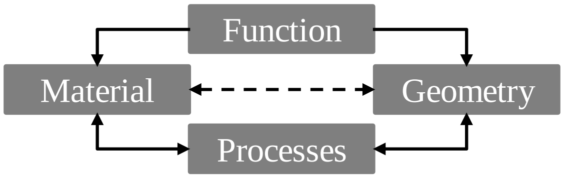
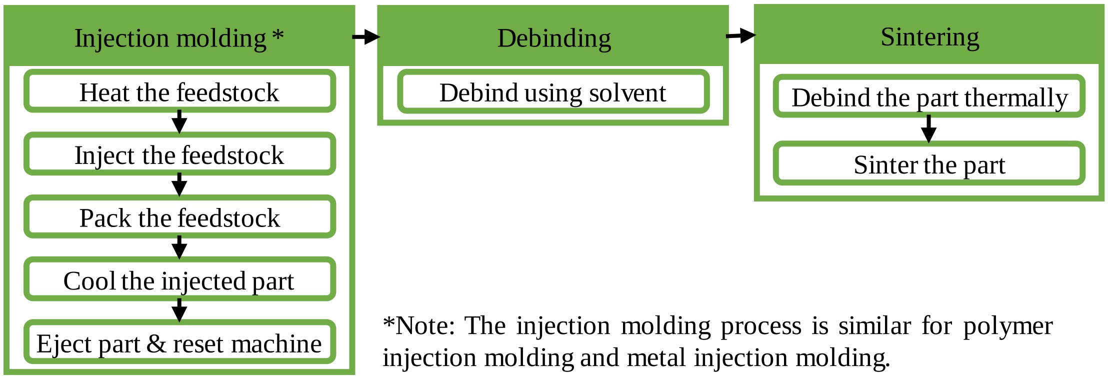


Figure 18. Function-material-geometry-processes relationship

Injection molding has a wide range of applications in manufacturing different types, sizes, and shapes of automotive, consumer, and industrial plastic products [76] and is selected for production of the polymer hexacopter shells due to its flexibility and reliability in creating high volumes of plastic parts. For making the propellers, metal injection molding (MIM), a powder metallurgy process that has been applied in industry since the 1970s [134], is utilized. Similar to polymer injection molding, MIM is amenable to the repeatable production of high quality, complex geometry metal parts, usually having small geometries. Since electronic components for the multicopters defined in the product development phase will be purchased from outside suppliers, the impact of their manufacture is expected to be independent of the other design modifications and not considered in this analysis.

Next, in order to **develop numerical models** of the processes, their equipment and operational characteristics must be understood. MIM is in the mass conserving category of the taxonomy of manufacturing processes [135]. The process shapes a metal powder and polymer feedstock into the desired geometry by injecting material into a shaped mold under pressure [136]. The MIM process flow is presented in Figure 19; it shares the same initial process steps as polymer injection molding.



*Note: The injection molding process is similar for polymer injection molding and metal injection molding.

Figure 19. Metal injection molding process flow

The injection molding step starts with heating the feedstock, followed by injecting it into a mold cavity, a negative of the product being designed, through runner and gating system. When packed, the feedstock has time to cool in the mold cavity. Next, the mold opens and the solidified part is ejected from the mold. The machine is then reset for the next cycle.

In the MIM process flow, after injection molding, the primary debinding step removes the primary binders, most commonly using an organic or water-based solvent, or by applying catalytic debinding [137]. Primary debinding is followed by thermal debinding and sintering to remove secondary binders and to make a strong, densified metal product. The process causes part shrinkage, which must be controlled to meet the desired dimensions and tolerances. It should be noted that primary debinding creates a network of pores, enabling the secondary binder to be evacuated during the next step. Secondary binder is removed at a higher temperature, and is required to keep the metal powders in place until diffusion bonding at high sintering temperatures.

In polymer injection molding, a thermoplastic polymer is heated to a highly plastic state and pushed under pressure into a mold, where it solidifies in the shape defined by the mold cavity [138]. The process flow for the polymer injection molding does not require debinding and sintering and is exactly similar to the injection molding step in the metal injection molding process.

With the UMPs selected and basic functions understood, numerical models are developed to support the sustainability assessment to be performed in Phase 4. The MaPS Sustainability Assessment Tool contains numerical input-output models for metal extrusion [138] (Appendix A), polymer injection molding [76] (Appendix B), drilling [67] (Appendix C), and milling [61] (Appendix D). The numerical model to estimate the energy consumption of the metal injection molding (MIM) process [49] is developed and presented below. A unit process consists of the inputs of the process, the process itself, and the outputs of the process [60,61]. A simplified input-output process diagram for the MIM unit process is presented in Figure 20.

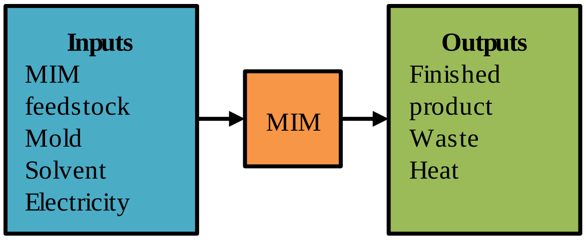


Figure 20. Input-Output diagram of a MIM process generating the LCI data

The concept of unit operations is applied in this research to estimate MIM process energy use. The UPLCI model presented herein is developed based on a representative operational sequence, as follows:

1. *Basic time* is used to calculate the basic energy consumed by injection molding machine during its on state, but when it is not performing any manufacturing operations (e.g., to keep displays operating). It includes:

- Loading the injection molding machine with the feedstock, and

Process set-up, which occurs once at the beginning of a production run. The set-up time is divided by the number of parts in the run (assumed to be negligible) [139].

2. *Injection time* is used to calculate the energy consumed by the injection unit. It includes:

- Heating the feedstock using heaters around the reciprocating screw barrel,
- Injecting the heated feedstock (shot) into the mold cavity using the screw, and
- Packing of additional feedstock into the mold cavity as the shot cools and shrinks.

3. *Clamping time* is used to calculate the energy consumed by the clamping unit while cooling the injected part to the eject temperature and resetting the machine for the next cycle (i.e., opening/ejecting, closing, and clamping). This differs from other UPLCI models, where part unloading is within basic time; here, it is an automated operation of the machine.

Energy consumption for the MIM process is characterized using many variables, including parameters for material properties and machine specifications [140]. These parameters include:

1. Process set-up occurs once at the beginning of a batch of workpieces to be processed. The set-up time is divided by the total number of parts processed and is assumed to be negligible [139].
2. Loading the injection molding machine with the feedstock and the mold (basic time)
3. Heating the feedstock by heaters around the reciprocating screw barrel idle time)
4. Injection molding (cycle time).
5. Unloading the injection molding machine is considered as resetting. Thus, it is not considered as part of the basic time.
6. Loading the solvent debinding oven with green parts (basic time)
7. Primary debinding time (cycle time)
8. Unloading the debinding system (basic time)
9. Loading the sintering furnace with brown parts (basic time)
10. Secondary debinding and sintering (cycle time)
11. Unloading the sintering furnace (basic time)

As mentioned above, polymer and metal injection molding processes have similar process steps in the injection molding process. Thus, a numerical model for characterizing the energy consumption of the polymer injection molding by Madan et al. [76] was used herein as the basis to develop the numerical model for the MIM process. Madan et al. [76] validated their injection molding model by comparing their modeled process energy use with reported process energy use. They applied industry-driven benchmarks (e.g., industry averages and best practices) based on published information related to the technologies considered (e.g., injection molding machines). Their analysis indicated that their estimated energy consumptions and their associated values are approximately 10-20% different. Moreover, the primary method for determining MIM process energy applies equations developed from first principles. These transformation equations, which model the conversion of inputs to outputs, numerically describe the basic, injection, and clamping energies. These transformations are highly dependent on the properties of the materials used as well as the specifications of the machine used. Some sub-processes in injection and clamping are more difficult to characterize due to a dearth of high-quality data and usable models reported in the literature. However, energy characterizations can be simplified by describing the relation between power and time for each sub-process. Overall MIM process energy use, E_{MIM}, is summarized in eq. 5:

$$\mathrm{E_{MIM}} = \mathrm{E_{basic}} + \mathrm{E_{injection}} + \mathrm{E_{clamping}} \tag{5}$$

Basic energy is consumed over the entire process cycle and during standby. Per part basic energy consumption for injection molding (eq. 6) is the basic power rating of the machine multiplied by injection molding basic time, which is divided by the number of mold cavities. Prior work has studied injection molding machine energy use [141–

146]; the typical basic power is reported as 4% of the machine power for electric machines and 2% for hydraulic machines [147].

$$\mathrm{E_{basic(IM)}} = \left(\mathrm{P_{basic(IM)}} \times \mathrm{t_{basic(IM)}}\right)/\mathrm{n_{cav}} \tag{6}$$

Injection energy is required to melt the feedstock and inject and pack this plasticized material into the mold at a metered rate. Total injection energy is divided by the number of mold cavities to obtain the per-part injection energy (eq. 7).

$$\mathrm{E_{injection}} = \left(\mathrm{E_{melt}} + \mathrm{E_{mat\_inj}} + \mathrm{E_{pack}}\right)/\mathrm{n_{cav}} \tag{7}$$

The energy needed to melt the required shot volume is presented in eq. 8. The feedstock for MIM is generally a mixture of metal powder and a binder comprised of different constituents (i). The energy consumed by each constituent is considered individually. Consequently, the binder melting energy is the sum of the melting energy for each component.

$$\mathrm{E_{melt}} = \sum\left[\rho_\mathrm{i} \times \mathrm{V_i} \times \left[\mathrm{C_{pi}} \times \left(\mathrm{T_{inj}} - \mathrm{T_{am}}\right) + \mathrm{H_{fi}}\right]\right] + \rho_\mathrm{m} \times \mathrm{V_m} \times \left[\mathrm{c_{pm}} \times \left(\mathrm{T_{inj}} - \mathrm{T_{am}}\right)\right] \times (\mathrm{c_1}/\eta_\mathrm{screw} + (1 - \mathrm{c_1})/\eta_\mathrm{heater}) \tag{8}$$

The parameters needed to determine melting energies of the constituents are their respective densities, volumes, heat capacities, and heats of fusion. The density for a multi-constituent material can be calculated using eq. 9 [139]:

$$\rho_\mathrm{f} = 1/(\mathrm{X_b}/\rho_\mathrm{b} + \mathrm{X_m}/\rho_\mathrm{m}) \tag{9}$$

The binder melting energy is added to the energy required to heat the metal powder to the injection temperature. The heat of fusion for the metal powder is not considered, since metal does not melt at injection molding temperatures. Energy required for the feedstock to reach injection (melting) temperature may also be estimated using empirically derived values for specific heat (e.g., through differential scanning calorimetry).

Theoretical energy required for material injection is shown in eq. 10, and is the product of injection pressure and shot volume [76]. Injection pressure for different materials is usually provided by the manufacturer of the MIM machine.

$$\mathrm{E_{mat\_inj}} = \left(\mathrm{p_{inj}} \times \mathrm{V_{shot}}\right)/\eta_{\mathrm{screw}} \tag{10}$$

The theoretical energy required to pack the part is shown in eq. 11, and is the packing (holding) pressure multiplied by the shot volume and the parameter ε (change in volume per unit volume of feedstock, given a decrease in temperature).

$$\mathrm{E_{pack}} = \left(\mathrm{c_2} \times \mathrm{p_{inj}} \times \mathrm{V_{shot}} \times \varepsilon\right)/\eta_{\mathrm{screw}} \tag{11}$$

The calculation for ε is shown in (eq. 12) [76], and multiplies an empirical constant (c_3) by the binder thermal expansion coefficient and the difference in injection and ejection temperatures.

$$\varepsilon = \mathrm{c_3} \times \alpha \times \left(\mathrm{T_{inj}} - \mathrm{T_{ej}}\right) \tag{12}$$

The time to inject and pack material feedstock into the mold (eq. 13) is calculated by dividing the total shot volume by the average flow rate of material into the mold [76].

$$t_i = V_{shot}/Q_{avg} \tag{13}$$

Calculation of the material shot volume, which is the total volume of material injected and packed into the mold (eq. 14), accounts for the total part volume, the volume of material contained in the gating system, and expected material shrinkage.

$$V_{shot} = V_{part} \times (1 + \varepsilon + \Delta) \times n_{cav} \tag{14}$$

The average flow rate of feedstock material into the mold (eq. 15) is the theoretical maximum material flow rate (eq. 16) multiplied by a factor (c_4) that accounts for varying material flow rate during the process, e.g., due to varying material cooling properties and mold designs.

$$Q_{avg} = c_4 \times Q_{max} \tag{15}$$

$$Q_{max} = P_{inj}/p_{inj} \tag{16}$$

The machine injection power is reported in the equipment specifications. Injection pressure is dependent on the feedstock type and part geometry, and can be determined experimentally or analytically through computational modeling.

Total cycle time (eq. 17) for the MIM process is the summation of injection time, cooling time, and resetting time. Cooling time is typically 50% - 80% of the total cycle time [148].

$$t_{cycle(MIM)} = t_i + t_c + t_r \tag{17}$$

Per part energy consumption for the clamping unit during idle time (eq. 18) is defined as the summation of the cooling and resetting energies divided by the number of cavities in the mold.

$$E_{clamping} = (E_{cool} + E_{reset})/n_{cav} \tag{18}$$

The energy used to cool the part to the minimum required ejection temperature is shown in eq. 19. It is calculated by dividing the heat to be removed from the part by the coefficient of performance of the cooling equipment [76].

$$E_{cool} = (H_{cool}/COP)/\eta_{cool} \tag{19}$$

Heat to be removed is the product of the specific heat and mass of the feedstock material used in the shot, multiplied by the difference in the injection and ejection temperatures (eq. 20).

$$H_{cool} = \sum \left[\rho_i \times V_i \times \left[C_{pi} \times \left(T_{inj} - T_{ej}\right) + H_{fi}\right]\right] + \rho_m \times V_m \times \left[c_{pm} \times \left(T_{inj} - T_{ej}\right)\right] \tag{20}$$

The time required to cool the part to the ejection temperature is described in eq. 21, which assumes one-dimensional heat conduction, and considers the maximum wall thickness, thermal diffusivity, and expected temperature differences [149].

$$\mathrm{t_c} = \left(\frac{\mathrm{h_{max}^2}}{\pi^2 \times \gamma}\right) \times \ln\left(\frac{4}{\pi}\right) \times \left(\frac{\mathrm{T_{inj}} - \mathrm{T_m}}{\mathrm{T_{ej}} - \mathrm{T_m}}\right) \tag{21}$$

A parameter of particular interest in calculating the cooling time is thermal diffusivity of the feedstock material, as defined in eq. 22.

$$\gamma_\mathrm{f} = \lambda_\mathrm{f} / \left(\rho_\mathrm{f} \times \mathrm{c_p}\right) \tag{22}$$

In MIM, the feedstock is a mixture of binder and metal powder. Thermal conductivity of a mixture can be determined experimentally or approximated using Maxwell's model of mixtures [150] to account for the different thermal conductivities of the binder (λ_b) and the metal powder (λ_m), as shown in eq. 23.

$$\lambda_\mathrm{f} = \lambda_\mathrm{b} \times \left(\frac{\lambda_\mathrm{m} + 2 \times \lambda_\mathrm{b} + 2 \times \mathrm{X_m} \times (\lambda_\mathrm{m} - \lambda_\mathrm{b})}{\lambda_\mathrm{m} + 2 \times \lambda_\mathrm{b} - \mathrm{X_m} \times (\lambda_\mathrm{m} - \lambda_\mathrm{b})}\right) \tag{23}$$

The energy for resetting the machine is presented in eq. 24, which has three components: the energy to shut the mold, open the mold, and eject the part. These three sub-processes typically account for less than one quarter (c_5<0.25) of the total energy used for material injection (E_{mat_inj}), cooling (E_{cool}), and melting (E_{melt}) [151].

$$\mathrm{E_{reset}} = \mathrm{c_5} \times \left(\mathrm{E_{mat\_inj}} + \mathrm{E_{cool}} + \mathrm{E_{melt}}\right) / \eta_\mathrm{clamp} \tag{24}$$

Resetting time is shown in eq. 25, and is derived from the kinematics of the clamping system. It considers dwell time (the time for the molded part to fall from the mold), dry cycle time (the total time taken to open and close the empty mold), the depth of the part, clearance distance for part removal (user-defined), clamp stroke length, and mold opening (c_6) and closing (c_7) factors [149].

$$\mathrm{t_r = t_{dwell} + (c_6 + c_7) \times t_{dry} \times \sqrt{\frac{2 \times d_{cav} + d_{cl}}{L_s}}} \tag{25}$$

Finally, with the numerical models developed for the selected UMPs, we must **define the process parameters**. The optimal powder loading for 316L stainless steel is estimated to be around 60% by volume, with 40% binder in the MIM feedstock [152,153]. The binder to be used in the feedstock has the composition presented in Table 10. The density for stainless steel is 7.881 g/cc and the calculated density for the selected binder is 1.11 g/cc [154]. Thus, the mass fraction for the metal powder in this case is 91.4%, and the mass fraction for the binder is 8.6%. Using these values, the density of the injection molding feedstock is 5.17 g/cc [155].

Table 10. Selected binder composition [154]

Designation	Fraction (%)	Melting Temp. (°C)	Density (gr/cc)
PMMA	65	157.8	1.19
PEG	8	35-40	1.22
Paraffin	25	60-62	0.9
Stearic acid	2	70.1	0.94

The metal injection molding machine specifications and process parameters to be used are presented in Table 11. The selected product and process design parameters for propellers in PD1 and PD2 are reported in Table 12 and Table 13, respectively.

Table 11. Selected metal injection molding machine specifications and process parameters for propellers in PD1 and PD2

Type	Variable	Unit	Specified value/range	Selected value	Source
Max clamp stroke	L_s	m	0.45	0.45	[156]
Injection pressure	p_{inj}	MPa	152-250	201	[156]
Injection temperature	T_{inj}	°C	120-150	135	[157]
Ejection temperature	T_{ej}	°C	80-120	100	[139]
Ambient temperature	T_{amb}	°C	18-22	20	-
Mold temperature	T_m	°C	40-80	60	[139]
IM machine injection power	P_{inj}	kW	23-46	34.5	[156]
IM basic power	$P_{basic(IM)}$	kW	1.4	1.4	[156]
Packing/holding pressure	P_{pack}	MPa	121-217	169	[154]
Dry cycle time for PD1	t_{dry}	s	1.5	1.5	[149]
Dry cycle time for PD2	t_{dry}	s	1	1	[149]
Dwell time for PD1	t_{dwell}	s	5	5	[149]
Dwell time for PD2	t_{dwell}	s	3	3	[149]
Max flow rate	Q_{max}	cm^3/s	0.172	0.172	[76]
Coefficient of performance	COP	kWh/kWh	2.25	2.25	[76]
Energy efficiency of cooling system	η_{cool}	%	80	80	[158]
Energy efficiency of screw motor	η_{screw}	%	87-95	91	[76]
Energy efficiency of barrel heater	η_{heater}	%	30-70	50	[159,160]
Energy efficiency of clamp motor	η_{clamp}	%	87-95	91	[76]

Table 12. Selected product and process parameters for propellers in PD1 [76]

Type	Variable	Units	Value
Fraction of melting energy from the screw	c_1	%	75
Fraction of equivalent injection pressure	c_2	%	75
Empirical constant for calculating shrinkage	c_3	-	3
Factor accounting for varying flow rate	c_4	%	50
Fraction of energy due to resetting	c_5	%	25
Mold opening rate factor	c_6	-	1.25
Mold closing rate factor	c_7	-	0.5
Heat capacity of PMMA	c_{p1}	kJ/kg°C	1.5
Heat capacity of PEG	c_{p2}	kJ/kg°C	2.2
Heat capacity of paraffin	c_{p3}	kJ/kg°C	2.9
Heat capacity of stearic acid	c_{p4}	kJ/kg°C	2.3
Heat capacity of 316L powder	c_{pm}	kJ/kg°C	0.5
Depth of the mold cavity	d_{cav}	cm	1.0
Clearance between mold and part	d_{cl}	cm	10.0
Heat of fusion for PMMA	H_{f1}	kJ/kg	355
Heat of fusion for PEG	H_{f2}	kJ/kg	180
Heat of fusion for paraffin	H_{f3}	kJ/kg	210
Heat of fusion for stearic acid	H_{f4}	kJ/kg	198
Heat of fusion for 316L powder	H_m	kJ/kg	285
Maximum wall thickness of the part	h_{max}	mm	3.0
Number of cavities	n_{cav}	integer	1.0
Volume of the propellers	V_{part}	cm^3	7.55
Volume of the binder	V_{binder}	cm^3	3.02
Volume of PMMA	V_1	cm^3	1.96
Volume of PEG	V_2	cm^3	0.24
Volume of paraffin	V_3	cm^3	0.76
Volume of stearic acid	V_4	cm^3	0.06
Volume of 316L powder	V_m	cm^3	4.53
Coefficient of thermal expansion for PMMA	α	cm/cm*°C	$7.5E10^{-5}$
Fraction of part volume in the gating system	Δ	%	20
Density of 316L stainless steel	ρ_m	kg/m^3	7881
Thermal conductivity	λ	W/m*°C	2.70
Thermal diffusivity of the material	γ	m^2/s	0.75

Table 13. Selected product and process parameters for propellers in PD2 [76]

Type	Variable	Units	Value
Fraction of melting energy from the screw	c_1	%	75
Fraction of equivalent injection pressure	c_2	%	75
Empirical constant for calculating shrinkage	c_3	-	3
Factor accounting for varying flow rate	c_4	%	50
Fraction of energy due to resetting	c_5	%	25
Mold opening rate factor	c_6	-	1.25
Mold closing rate factor	c_7	-	0.5
Heat capacity of PMMA	c_{p1}	kJ/kg°C	1.5
Heat capacity of PEG	c_{p2}	kJ/kg°C	2.2
Heat capacity of paraffin	c_{p3}	kJ/kg°C	2.9
Heat capacity of stearic acid	c_{p4}	kJ/kg°C	2.3
Heat capacity of 316L powder	c_{pm}	kJ/kg°C	0.5
Depth of the mold cavity	d_{cav}	cm	1.0
Clearance between mold and part	d_{cl}	cm	5.0
Heat of fusion for PMMA	H_{f1}	kJ/kg	355
Heat of fusion for PEG	H_{f2}	kJ/kg	180
Heat of fusion for paraffin	H_{f3}	kJ/kg	210
Heat of fusion for stearic acid	H_{f4}	kJ/kg	198
Heat of fusion for 316L powder	H_m	kJ/kg	285
Maximum wall thickness of the part	h_{max}	mm	3.0
Number of cavities	n_{cav}	integer	1.0
Volume of the propellers	V_{part}	cm^3	3.77
Volume of the binder	V_{binder}	cm^3	1.51
Volume of PMMA	V_1	cm^3	0.98
Volume of PEG	V_2	cm^3	0.12
Volume of paraffin	V_3	cm^3	0.38
Volume of stearic acid	V_4	cm^3	0.03
Volume of 316L powder	V_m	cm^3	2.26
Coefficient of thermal expansion for PMMA	α	cm/cm*°C	$7.5E10^{-5}$
Fraction of part volume in the gating system	Δ	%	20
Density of 316L stainless steel	ρ_m	kg/m^3	7881
Thermal conductivity	λ	W/m*°C	2.70
Thermal diffusivity of the material	γ	m^2/s	0.75

The polymer injection molding machine specifications and process parameters to be used are presented in Table 14. The selected product and process design parameters for shells in PD1 and PD2 are reported in Table 15 and Table 16, respectively.

Table 14. Selected metal injection molding machine specifications and process parameters for shells in PD1 and PD2

Type	Variable	Unit	Selected value
Clamping force	F	kN	
Injection pressure	p_{inj}	MPa	130
Injection temperature	T_{inj}	°C	230
Ejection temperature	T_{ej}	°C	102
Ambient temperature	T_{amb}	°C	23
Mold temperature	T_m	°C	50
Polymer machine injection power	P_{inj}	kW	5.5
Polymer basic power	$P_{basic(IM)}$	kW	0.25
Dry cycle time for PD1	t_{dry}	s	1.7
Dry cycle time for PD2	t_{dry}	s	1.0
Dwell time for PD1	t_{dwell}	s	5.0
Dwell time for PD2	t_{dwell}	s	3.0
Energy efficiency of the machine	η_{cool}	%	81

Table 15. Selected product and process design parameters for shells in PD1

Type	Variable	Units	Value
Fraction of equivalent injection pressure	c_2	%	75
Empirical constant for calculating shrinkage	c_3	-	3
Factor accounting for varying flow rate	c_4	%	50
Fraction of energy due to resetting	c_5	%	25
Mold opening rate factor	c_6	-	1.25
Mold closing rate factor	c_7	-	0.5
Heat capacity of polymer	c_{p1}	J/kg K	2050
Depth of the mold cavity	d_{cav}	cm	1
Clearance between mold and part	d_{cl}	cm	5
Number of cavities	n_{cav}	integer	1
Volume of the shells	V_{part}	cm^3	43.67
Coefficient of thermal expansion for PMMA	α	m/m*°K	$7.4E10^{-5}$
Fraction of part volume in the gating system	Δ	%	20
Thermal conductivity	λ	W/m*°K	0.176

Table 16. Selected product and process design parameters for shells in PD2

Type	Variable	Units	Value
Fraction of equivalent injection pressure	c_2	%	75
Empirical constant for calculating shrinkage	c_3	-	3
Factor accounting for varying flow rate	c_4	%	50
Fraction of energy due to resetting	c_5	%	25
Mold opening rate factor	c_6	-	1.25
Mold closing rate factor	c_7	-	0.5
Heat capacity of polymer	c_{p1}	J/kg K	2050
Depth of the mold cavity	d_{cav}	cm	1
Clearance between mold and part	d_{cl}	cm	3
Number of cavities	n_{cav}	integer	1
Volume of the shells	V_{part}	cm^3	38.35
Coefficient of thermal expansion for PMMA	α	m/m*°K	$7.4E10^{-5}$
Fraction of part volume in the gating system	Δ	%	20
Thermal conductivity	λ	W/m*°K	0.176

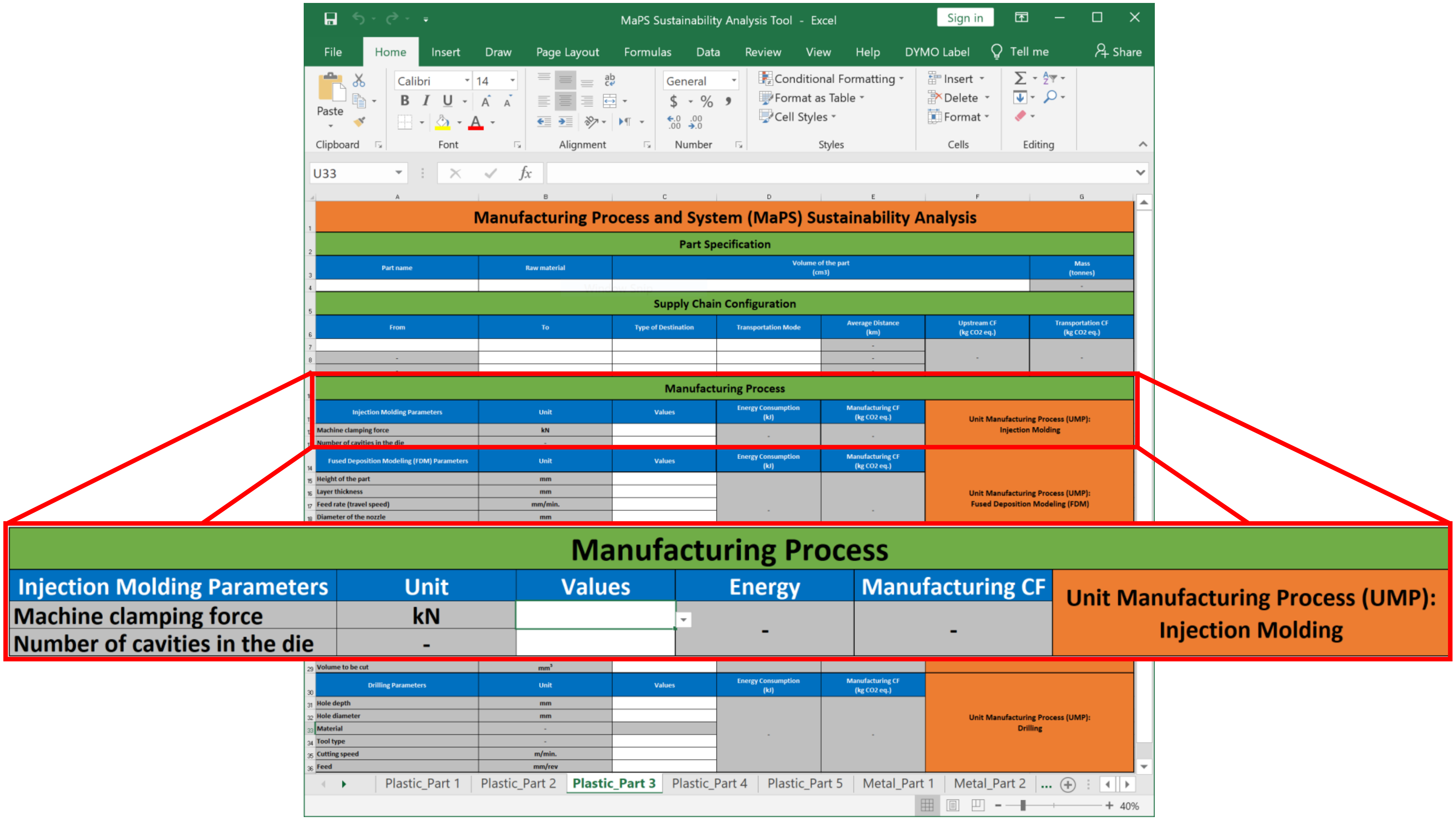
In addition to transportation activities, NOII and DAW values (Eqs. 3 and 4) must be determined for manufacturing. While transportation time was used in the calculation of $NOII_{trans}$, to determine $NOII_{mfg}$, process cycle time (T_{mfg}) is multiplied by the production volume (PV) and the rate of nonfatal occupational injuries and illnesses ($RNOII_{mfg}$) reported by the BLS for various industries [133]. This value, as represented in Eq. 26, is divided by 200,000 hours, which is assumed as the annual working hours for 100 equivalent full-time workers.

$$NOII_{mfg} = RNOII_{mfg}.\left(\frac{t_{mfg}.PV}{200000}\right) \tag{26}$$

To calculate DAW (Eq. 27), the percentage of injuries and illnesses that result in days away from work must first be determined. The percentage is provided by dividing the rate of days away from work (RDAW) by the rate of nonfatal occupational injuries and illnesses (RNOII) for the relevant industry segment from BLS data. This ratio is then multiplied by $NOII_{mfg}$ to provide the total number of cases resulting in days away from work. Finally, this quantity is multiplied by the median days away from work (MDAW), from BLS data, to provide the total number of days away from work for each manufacturing activity.

$$DAW_{mfg} = \left(\frac{RDAW_{mfg}}{RNOII_{mfg}}\right).NOII_{mfg}.MDAW_{mfg} \tag{27}$$

Similar to the other modules, users can provide information for the Manufacturing Process module using drop-down menus. This module captures the values for the key process parameters used for making the product. Moreover, it uses the information provided by the Part Specification (e.g., mass) and Supply Chain Configuration (e.g., the manufacturing location) modules to estimate the energy consumption and the manufacturing carbon footprint. A screenshot of the Manufacturing Process module is presented in Figure 21.



Manufacturing Process and System (MaPS) Sustainability Analysis

Part Specification

Part name	Raw material	Volume of the part (cm3)	Mass (tonnes)
			-

Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		

Manufacturing Process

Injection Molding Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Machine clamping force	kN		-	-	Unit Manufacturing Process (UMP): Injection Molding
Number of cavities in the die	-				

Fused Deposition Modeling (FDM) Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Height of the part	mm		-	-	Unit Manufacturing Process (UMP): Fused Deposition Modeling (FDM)
Layer thickness	mm				
Feed rate (travel speed)	mm/min.				
Diameter of the nozzle	mm				

Manufacturing Process

Injection Molding Parameters	Unit	Values	Energy	Manufacturing CF	Unit Manufacturing Process (UMP): Injection Molding
Machine clamping force	kN		-	-	
Number of cavities in the die	-				

Volume to be cut	mm^3				

Drilling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Hole depth	mm		-	-	Unit Manufacturing Process (UMP): Drilling
Hole diameter	mm				
Material	-				
Tool type	-				
Cutting speed	m/min.				
Feed	mm/rev				

Figure 21. Manufacturing Process module in the graphical user interface

4.4 Phase 4: Manufacturing Process and System (MaPS) Sustainability Analysis

The last phase of the integrated sustainability assessment framework developed herein is MaPS sustainability analysis, which aims to assess economic, environmental, and social impacts of the product. The activities of this phase are presented in Figure 22.

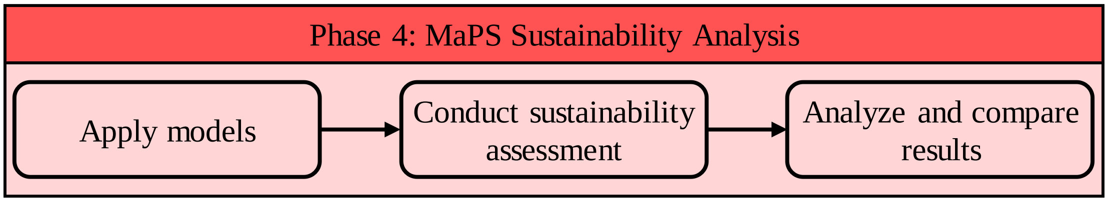
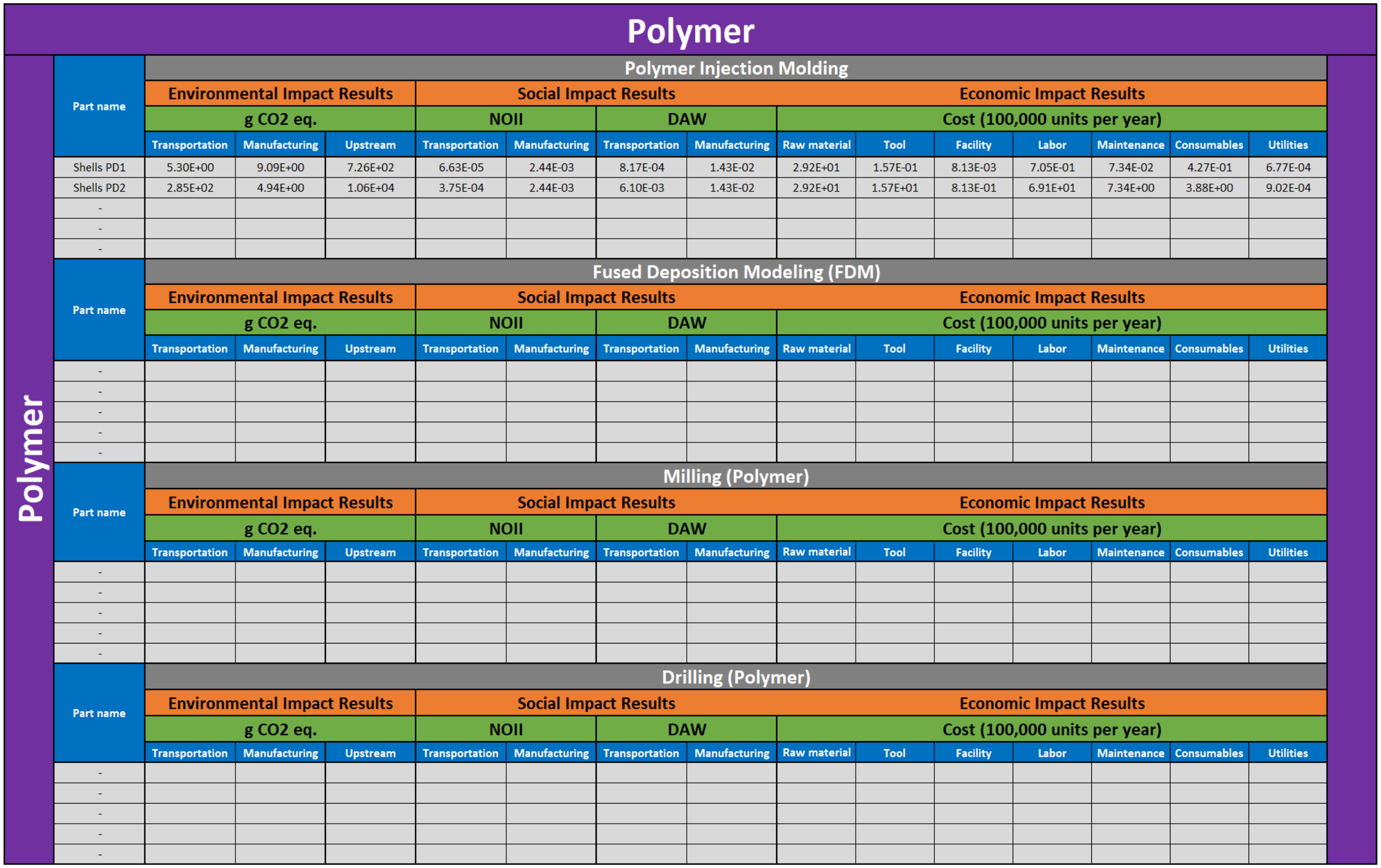


Figure 22. Activities under Phase 4 of the sustainability assessment framework

This phase starts with **applying the numerical models** for all the activities in the cradle-to-gate product life cycle scope using the input supply chain and manufacturing process information. However, as mentioned above, it is not expected that non-experts develop such models. Thus, the proof-of-concept MaPS Sustainability Analysis Tool is provided to apply developed models and **conduct the economic, environmental, and social impact assessments**. A screenshot of the tabular presentation of the results for the plastic parts are presented in Figure 23. In addition to the tabular presentation, pie charts are provided for the three aspects of sustainability, which are presented in detail in the next sub-sections. Presenting the information in this way enables the user to **analyze and compare the results** for different design, supply chain, and manufacturing alternatives.



Polymer

Polymer Injection Molding

Part name	Environmental Impact Results			Social Impact Results				Economic Impact Results							
	g CO2 eq.			NOII		DAW		Cost (100,000 units per year)							
	Transportation	Manufacturing	Upstream	Transportation	Manufacturing	Transportation	Manufacturing	Raw material	Tool	Facility	Labor	Maintenance	Consumables	Utilities
Shells PD1	5.30E+00	9.09E+00	7.26E+02	6.63E-05	2.44E-03	8.17E-04	1.43E-02	2.92E+01	1.57E-01	8.13E-03	7.05E-01	7.34E-02	4.27E-01	6.77E-04
Shells PD2	2.85E+02	4.94E+00	1.06E+04	3.75E-04	2.44E-03	6.10E-03	1.43E-02	2.92E+01	1.57E+01	8.13E-01	6.91E+01	7.34E+00	3.88E+00	9.02E-04
-														
-														
-														

Fused Deposition Modeling (FDM)

Part name	Environmental Impact Results			Social Impact Results				Economic Impact Results						
	g CO2 eq.			NOII		DAW		Cost (100,000 units per year)						
	Transportation	Manufacturing	Upstream	Transportation	Manufacturing	Transportation	Manufacturing	Raw material	Tool	Facility	Labor	Maintenance	Consumables	Utilities
-														
-														
-														
-														
-														

Milling (Polymer)

Part name	Environmental Impact Results			Social Impact Results				Economic Impact Results						
	g CO2 eq.			NOII		DAW		Cost (100,000 units per year)						
	Transportation	Manufacturing	Upstream	Transportation	Manufacturing	Transportation	Manufacturing	Raw material	Tool	Facility	Labor	Maintenance	Consumables	Utilities
-														
-														
-														
-														
-														

Drilling (Polymer)

Part name	Environmental Impact Results			Social Impact Results				Economic Impact Results						
	g CO2 eq.			NOII		DAW		Cost (100,000 units per year)						
	Transportation	Manufacturing	Upstream	Transportation	Manufacturing	Transportation	Manufacturing	Raw material	Tool	Facility	Labor	Maintenance	Consumables	Utilities
-														
-														
-														
-														
-														

Figure 23. Tabular presentation of the results for the plastic products in the MaPS Sustainability Analysis Tool

4.4.1 Economic Impact Assessment

Production cost models are required to compare the resulting cost of goods sold (COGS) for the two manufacturing process flows. A bottom-up cost modeling approach developed in prior work is applied herein [107,108,161]. Total COGS includes seven cost elements: tool, facility, labor, maintenance, raw materials, consumables, and utilities costs, which must be calculated for each UMP in the process flow. Common assumptions between the two processes are shown in Table 17. It was also assumed that one laborer performs injection molding in the metal injection molding process.

Table 17. Cost model assumptions: Model parameters

Parameter	Value
Cost of manufacturing space	\$1,000 /m^2
Facility amortization schedule	30 years
Equipment amortization schedule	10 years
Annual operator wages	\$50,000 /yr
Loaded labor cost rate	1.5x wages
Annual maintenance as a fraction of capital cost	5 %
Electricity cost	\$0.0641 /kWh

Development of the cost models requires a process step analysis, which includes capability and capacity analysis. Capability analysis considers *selection of a machine tool capable of implementing the process step*, while capacity analysis includes *calculating the cycle time for each process step and considering the correlation with the overall annual production required* [140].

The capability and capacity analyses, along with the cost data from vendors for each process step and raw material, enable calculation of the unit costs for each of the seven cost elements. The total unit cost (COGS for the two plates considered) can then be calculated based on the intended production volume (market size). Ultimately, market size and process utilization are key factors in determining COGS.

The production cost breakout by cost element for production volume of 1,000 and 100,000 propellers per year in PD1 and PD2 using metal injection molding process are presented in Figure 24 and Figure 25, respectively. Economic impact analysis results demonstrate that lower size of the propellers in PD2 lead to the lower raw material cost compared to PD1. Moreover, manufacturing process time in making the propellers of PD2 using metal injection molding is shorter than the propellers in PD1. Thus, the cost of utilities is lower in PD2. It should be noted that the mold needed in the injection molding process and the solvent required for the debinding process are considered under consumables. Since manufacturing process time and debinding time are higher for the propellers in PD1, the cost of consumables is higher compared to PD2, accordingly. However, as production volume increases, the mold and solvent costs are amortized over more products, consequently making the consumables cost lower for both product designs.

At low production volume, tool cost is the same and is the main cost driver for the both product designs. However, as production volume increases to 100,000 propellers per year, the tool cost for the propellers in PD2 becomes slightly lower compared to the propellers in PD1. This is mainly due to the shorter manufacturing process time for making the propellers in PD2, which increases the tool utilizations and consequently, reduced the number of tools required for making them at high production volume.

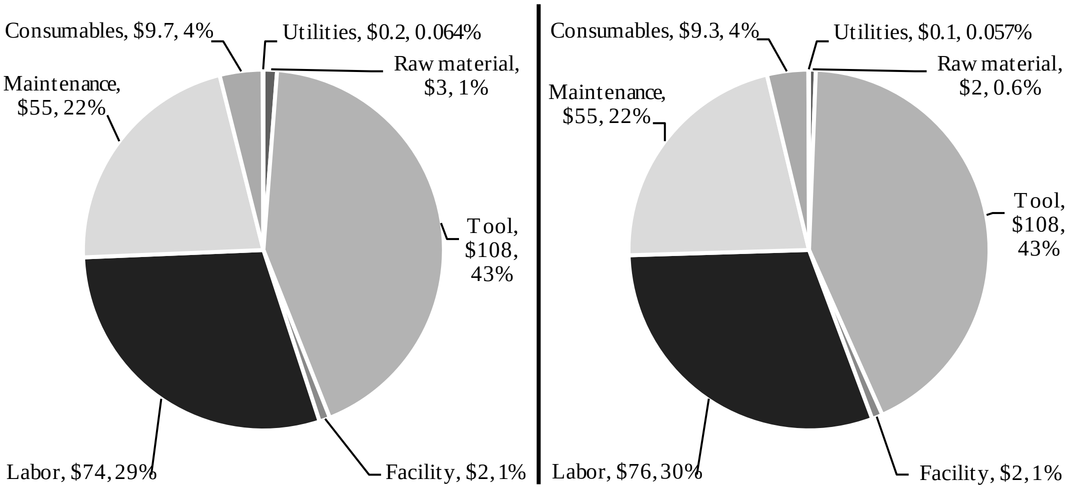


Figure 24. Unit cost breakout by category using metal injection molding for making the propellers in PD1 (left) and PD2 (right) (1,000 propellers/year)

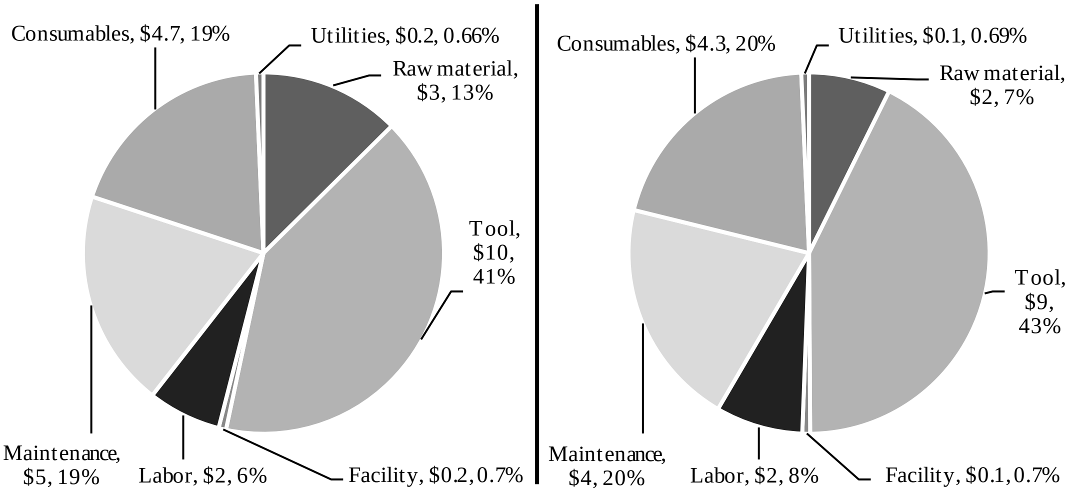


Figure 25. Unit cost breakout by category using metal injection molding for making the propellers in PD1 (left) and PD2 (right) (100,000 propellers/year)

The production cost breakout by cost element for production volume of 1,000 and 100,000 shells per year in PD1 and PD2 using polymer injection molding process are presented in Figure 26 and Figure 27, respectively.

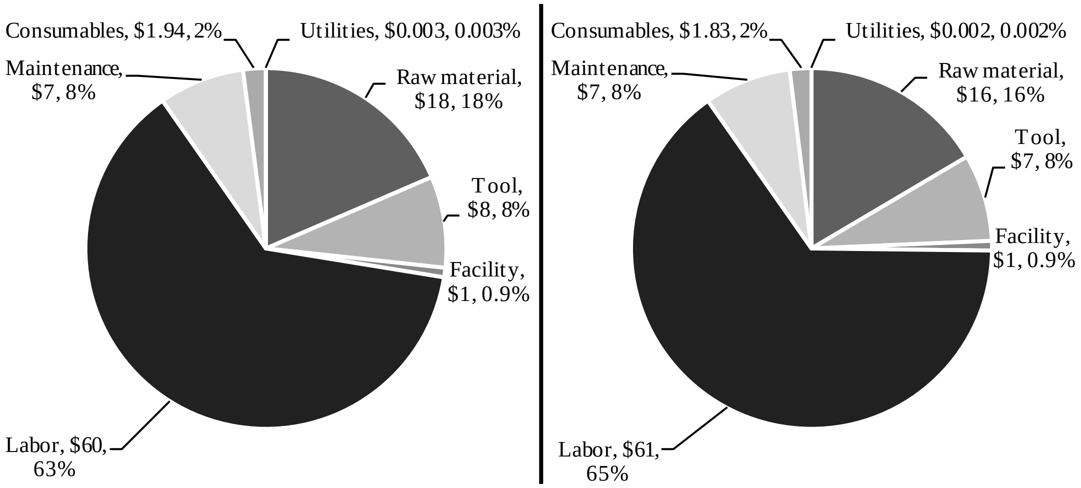


Figure 26. Unit cost breakout by category using injection molding for making the shells in PD1 (left) and PD2 (right) (1,000 shells/year)

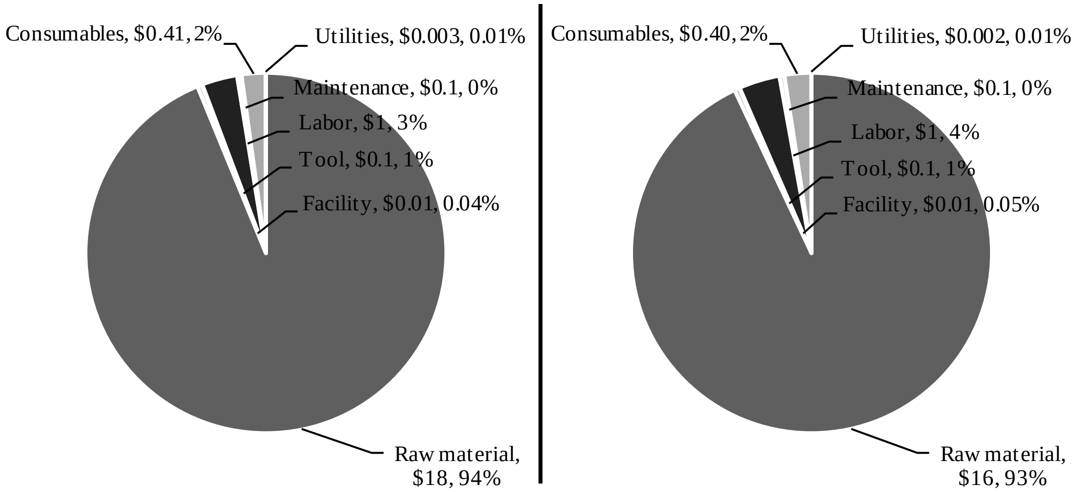


Figure 27. Unit cost breakout by category using injection molding for making the shells in PD1 (left) and PD2 (right) (100,000 shells/year)

While the raw material cost is the second cost driver at low production volume, as production volume increases it becomes the main cost driver for both product designs. The raw material cost for the shells in PD2 is lower due to the smaller size compared to the shells in PD1. Thus, manufacturing process time is shorter for the shells in PD2, which result in lower cost of utilities. Moreover, it leads to higher tool utilization in PD2, which makes the tool cost slightly lower compared to PD1.

While propellers are made using metal injection molding process and require three sets of tool to make the parts, shells are made using polymer injection molding process and require only injection molding tool. Thus, due to the lower number of tools required, tool cost is not a cost driver for the shells. In addition to the lower number of tools, polymer injection molding does not require solvent debinding. Thus, solvent is not needed for making the shells. However, similar to the metal injection molding process, mold is considered as a consumable for the polymer injection molding. Thus, as production volume increases, the cost of the mold is amortized over more products, making the consumables cost lower for both product designs. Comparing the cost of consumables, making the shells in PD2 has lower cost than PD1 at both production volumes.

4.4.2 Environmental Impact Assessment

Carbon footprint from transportation activities and manufacturing processes for making the propellers and the shells in PD1 and PD2 are presented in Figure 28 and Figure 29, respectively.

Environmental impact analysis results demonstrate that lower manufacturing process time for making the propellers in PD2 using metal injection molding process result in lower manufacturing carbon footprint compared to PD1. Similarly, transportation activities for the propellers in PD2 have shorter transportation time. This lowers the environmental impact of the transportation activities for the propellers in PD2, while the transportation mode in the supply chain of the propellers in PD2 has higher emission factor compared to the transportation modes for delivering the raw material from the supplier to the manufacturer of the propellers in PD1.

Similar to the propellers, the shells in PD2 have shorter manufacturing process time using polymer injection molding, which lowers the carbon footprint compared to the shells in PD1. The transportation modes in the supply chain of the shells in PD1 are deep-sea container, rail, and road, while air freight and road are the transportation modes in the supply chain of the shells in PD2. Since air freight has higher emission factor compared to the other transportation modes, transportation activities for the shells in PD2 have higher environmental impacts compared to the shells in PD1.

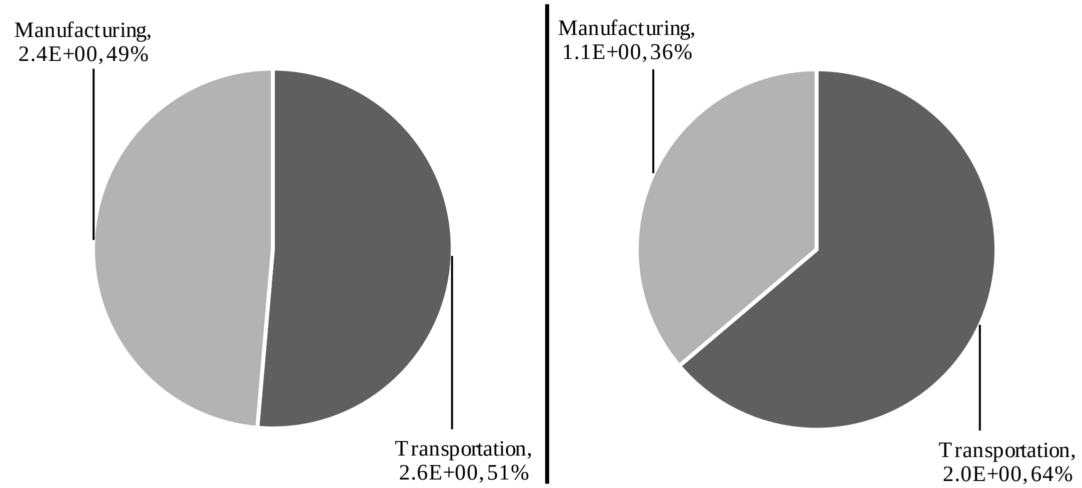


Figure 28. Carbon footprint of transportation and manufacturing processes for the propellers in PD1 (left) and PD2 (right)

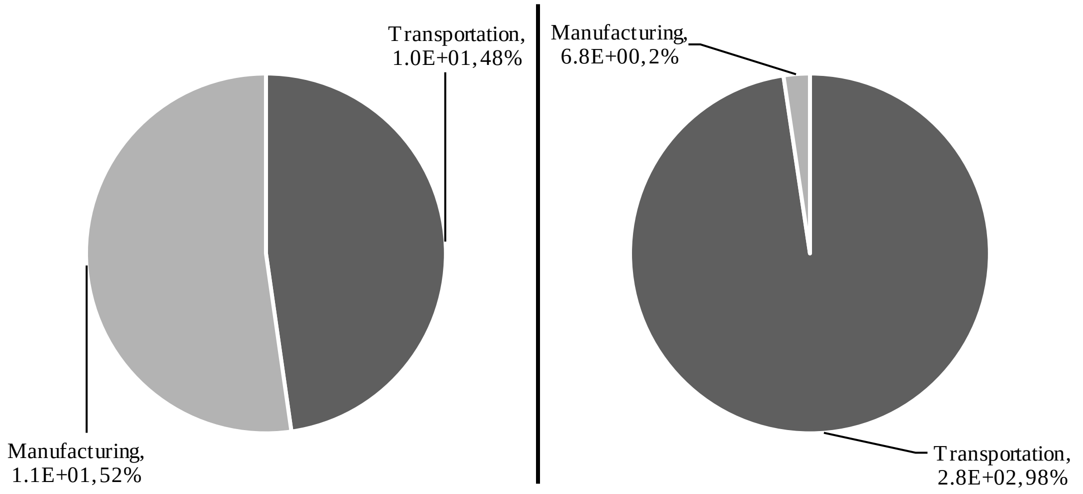


Figure 29. Carbon footprint of transportation and manufacturing processes for the shells in PD1 (left) and PD2 (right)

4.4.3 Social Impact Assessment

Nonfatal occupational injuries and illnesses analysis results of the transportation and manufacturing processes for the propellers and the shells in PD1 and PD2 under their associated supply chains are presented in Figure 30 and Figure 31, respectively.

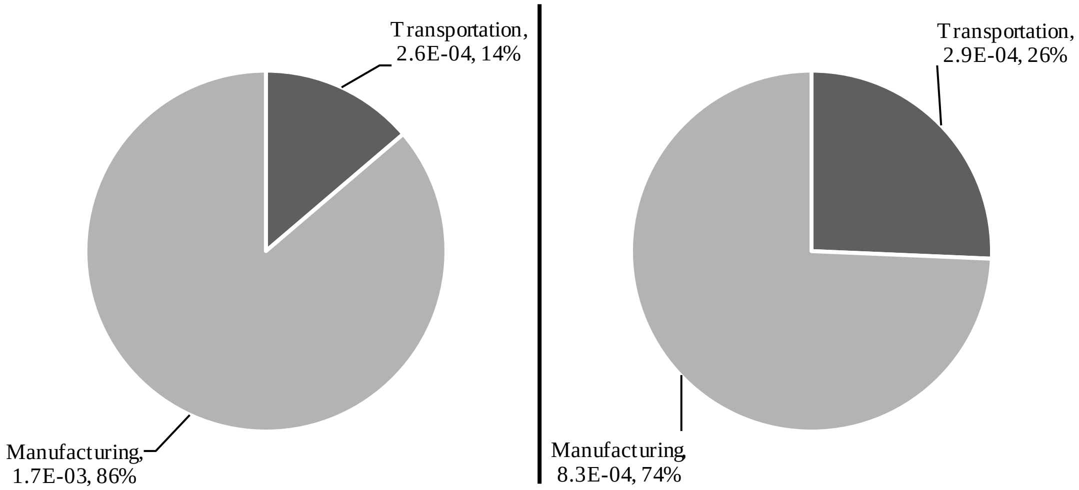


Figure 30. Nonfatal occupational injuries and illnesses from transportation and manufacturing processes for the propellers in PD1 (left) and PD2 (right)

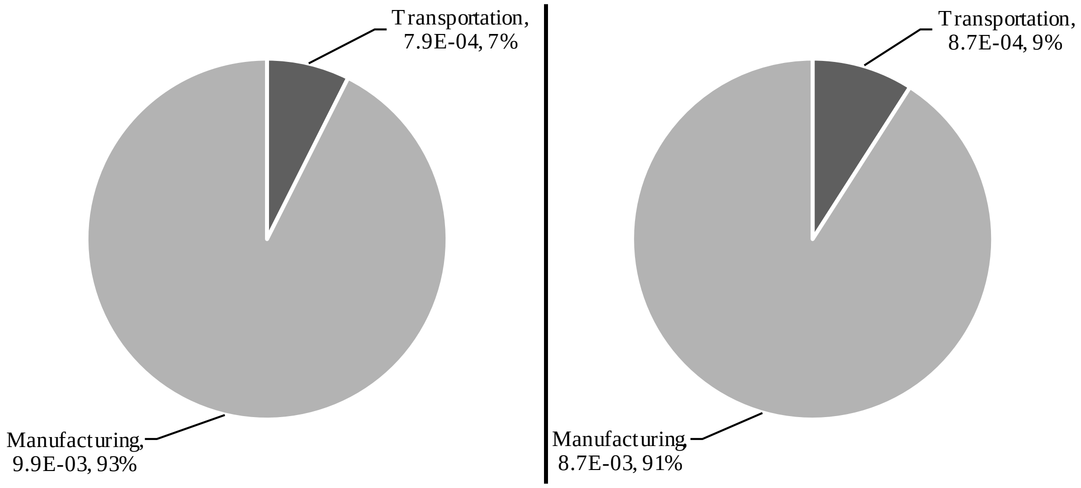


Figure 31. Nonfatal occupational injuries and illnesses from transportation and manufacturing processes for the shells in PD1 (left) and PD2 (right)

Days away from work analysis results of the transportation and manufacturing processes for the propellers and the shells in PD1 and PD2 under their associated supply chains are presented in Figure 32 and Figure 33, respectively.

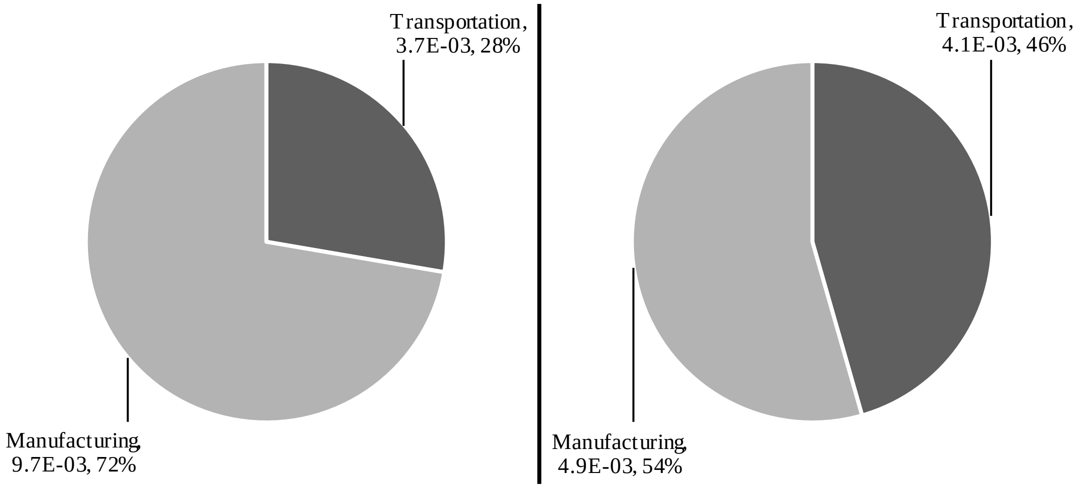


Figure 32. Days away from work due to transportation and manufacturing processes for the propellers in PD1 (left) and PD2 (right)

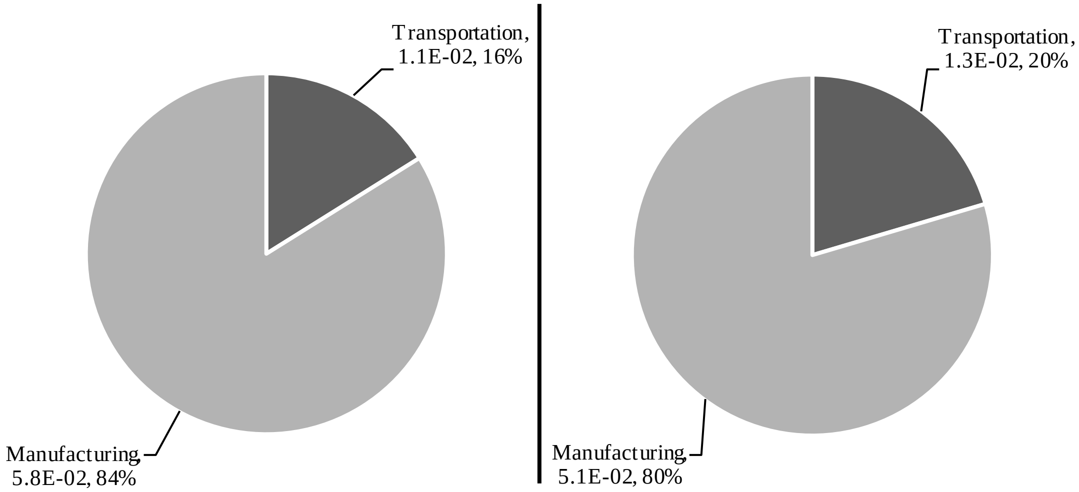


Figure 33. Days away from work due to transportation and manufacturing processes for the shells in PD1 (left) and PD2 (right)

Social impact analysis results demonstrate that lower manufacturing process time in making the propellers of PD2 using metal injection molding lead to reduced nonfatal occupational injuries and illnesses compared to PD1. For the transportation activities, propellers in PD2 have shorter transportation time. However, compared to the propellers in PD1, transportation activities have higher NOII in PD2. As summarized in Table 9, transportation modes to deliver the raw material to the manufacturer for the propellers in PD1 are rail, deep-sea container, and road. For the propellers in PD2, the transportation mode in the supply chain is road. Due to the lower rates of cases with days away from work in the transportation modes selected for the propellers in PD1, NOII has lower value compared to the propellers in PD2.

Similar to the propellers, the shells in PD2 are smaller compared to the shells in PD1. Thus, they have shorter manufacturing process time using polymer injection molding. This makes the value of nonfatal occupational injuries and illnesses lower for the manufacturing process in PD2. However, this is exactly opposite for the transportation activities. The transportation modes for the shells in PD1 are deep-sea container, rail, and road, while air freight and road are selected to deliver the raw material from the supplier to the manufacturer for the shells in PD2. Thus, transportation time for the shells in PD2 is shorter compared to PD1. However, due to the higher rates of cases with days away from work in the air freight transportation mode, nonfatal occupational injuries and illnesses have higher value for the transportation activities of the shells in PD2 compared to PD1.

As described above, the days away from work metric is calculated based upon nonfatal occupational injuries and illnesses. Thus, similar to the analysis of the nonfatal occupational injuries and illnesses, manufacturing process has lower days away from work for the propellers in PD2 compared to PD1. On the other hand, days away from work have higher value for the transportation activities of the propellers in PD2. Similarly, manufacturing processes have lower days away from work for the shells in PD2 compared to PD1. However, the value of the days away from work metric for the transportation activities of the shells in PD2 is higher compared to PD1. It should be noted that the severity of injuries and illnesses is assumed to be similar across manufacturing process types and transportation modes based on the U.S. BLS data. However, higher fidelity data (e.g., company-specific injury data) could elucidate variations in severity and lead to higher variations in DAW across the supply chain alternatives.

4.5 Discussion

A framework and a proof-of-concept tool are developed and described above, which facilitate manufacturing process and system sustainability assessment considering the economic (cost), environmental (carbon footprint), and social (nonfatal occupational injuries and illnesses as well as days away from work) aspects by non-experts (Table 18 and Table 19). To demonstrate the application of the framework within the MaPS Sustainability Analysis Tool, two multicopters were designed, making use of polymer and metal components. Thus, polymer injection molding and metal injection molding processes were selected to make the shells and propellers, respectively.

Table 18. Economic, environmental, and social impact assessment results for propellers and shells in PD1

Category	Economic ($)		Environmental (g CO_2 eq.)		Social (NOII)		Social (DAW)	
	1,000	100,000	Trans.	Mfg.	Trans.	Mfg.	Trans.	Mfg.
Propellers	252	24	2.6E+00	2.4E+00	2.6E-04	1.7E-03	3.7E-03	9.7E-03
Shells	96	19	1.0E+01	1.1E+01	7.9E-04	9.9E-03	1.1E-02	5.8E-02
Total	348	43	1.3E+01	1.4E+01	1.1E-03	1.2E-02	1.5E-02	6.8E-02

Table 19. Economic, environmental, and social impact assessment results for propellers and shells in PD2

Category	Economic (cost)		Environmental (g CO_2 eq.)		Social (NOII)		Social (DAW)	
	1,000	100,000	Trans.	Mfg.	Trans.	Mfg.	Trans.	Mfg.
Propellers	252	21	2.0E+00	1.1E+00	2.9E-04	8.3E-04	4.1E-03	4.9E-03
Shells	94	17	2.8E+02	6.8E+00	8.7E-04	8.7E-03	1.3E-02	5.1E-02
Total	346	38	2.9E+02	8.0E+00	1.2E-03	9.5E-03	1.7E-02	5.6E-02

As expected, it was found that process cycle time has significant impact on the sustainability performance. The smaller propellers and shells in product design 2 (PD2) resulted in shorter cycle time for the polymer and metal injection molding processes. In addition to the manufacturing processes, PD2 has shorter transportation time compared to PD1 due the selected transportation mode. Thus, the energy consumption and the associated carbon footprint for transportation and manufacturing activities are lower in PD2. The shorter manufacturing cycle time resulted in the lower number of injuries and illnesses as well as the days away from work in the manufacturing processes for PD2. However, due to the higher rates of injuries and illnesses in the transportation mode selected for PD2, it has higher social impacts.

Thus far, the first three research tasks have been discussed. The relevant methods and software tools for analyzing supply chain and manufacturing process sustainability performance for a given product are presented in Chapter 2. A framework was developed in Chapter 3 to integrate product design and supply chain information using a mechanistic, input-output unit manufacturing process modeling approach for quantifying manufacturing sustainability performance. In this chapter, the readily distributable, publicly-available MaPS Sustainability Analysis Tool was developed for non-experts to conduct manufacturing process and system analysis under the lens of sustainability performance. Next, Task 4 of this research aims to evaluate operational performance of the MaPS Sustainability Analysis tool, as discussed in Chapter 5.

Chapter 5: MaPS TOOL OPERATIONAL PERFORMANCE EVALUATION

As mentioned above, to fulfill the objective of this research, which is *to facilitate simultaneous analysis of sustainability performance impacts of different manufacturing processes and systems through unit manufacturing process modeling within an easy-to-use, publicly-available manufacturing process and system sustainability analysis tool*, four main tasks are pursued in this dissertation as follows:

- Task 1 (Chapter 2): Identify the relevant methods and software tools for analyzing product design, supply chain, and manufacturing process sustainability performance (i.e., environmental, economic, and social impacts);
- Task 2 (Chapter 3): Establish a framework that integrates product design and supply chain information within a mechanistic unit manufacturing process modeling approach for quantifying manufacturing sustainability performance;
- Task 3 (Chapter 4): Develop a publicly-available manufacturing process and system sustainability analysis tool for non-experts to conduct manufacturing process and system analysis under the lens of sustainability performance; and
- Task 4 (Chapter 5): Evaluate the operational performance of the manufacturing process and system sustainability analysis tool in terms of the ease-of-use and usefulness metrics.

Tasks 1, 2, and 3 have been discussed in the prior chapters, with Task 4 to be reported in this chapter. First, the method applied to evaluate the operational performance of the MaPS Sustainability Analysis Tool in terms of the ease-of-use and usefulness metrics is presented in Section 5.1. Next, the construction of the learning activities for evaluating the tool using this method is discussed in Section 5.2. Finally, the results and the analysis of tool performance are presented in Section 5.3.

5.1 Operational Performance Evaluation Method

Software evaluation methods are defined by Fernandez et al. [162] as

> "[P]rocedures composed by a series of well-defined activities to collect data related to the interaction between the end user and a software product, in order to determine how the specific properties of a particular software contribute to achieving specific goal."

Various evaluation methods have been developed for software tool usability. Researchers have applied software usability evaluation methods in different domains, such as health, e-commerce, and web applications, among others (e.g., [163–166]).

Paz et al. [167] recently conducted a systematic review of software usability evaluation methods. Their objectives were to identify the most widely used method(s) in evaluating the usability of a software as well as to identify the most commonly used methods for software usability evaluation in different domains. They identified 34 usability evaluation methods. Their findings indicated that survey/questionnaire-based methods are the most widely applied across all software domains. In the software development domain, they found that surveys/questionnaires, user testing, interviews, and user testing-thinking were the top four methods for evaluating the usability of a software, in decreasing order of use.

In line with the findings from Paz et al. [167], a survey/questionnaire-based method entitled *Technology Acceptance Model (TAM)* [168] is applied herein to evaluate the MaPS Sustainability Analysis Tool due to its technical simplicity and flexibility. TAM has been widely used in measuring users' attitudes towards a particular software tool technology [169]. The method does not require face-to-face meetings with the users to capture their feedback on the tool being evaluated. Thus, it helps to avoid the logistical issues such as difficulties in scheduling meetings with a sufficient number of users as well as delays in the study timeline. Most importantly, it evaluates the ease-of-use and usefulness metrics, which are fundamental determinants of the success of tool use [168]. Perceived usefulness is defined as *[t]he degree to which a person believes that using a particular system would enhance his or her job performance* [168]. Perceived ease-of-use is defined as *[t]he degree to which a person believes that using a particular system would be free of effort* [168].

Davis developed TAM using a rigorous step-by-step process [168]. First, 37 published research papers, which focused on user reactions to interactive systems, were identified and reviewed to identify the aspects of the ease-of-use and usefulness that should be evaluated. Next, based on the definitions of the perceived ease-of-use and usefulness, 14 candidate indicators were developed for the two metrics. The candidate indicators were developed in a way that they possess *content validity*, which is *[t]he degree to which the score or scale being used represents the concept about which generalizations are to be made* [170].

The candidate indicators were then refined by 15 pre-test participants, who were experienced computer users from the Sloan School of Management at MIT. The participants identified the indicators that best fit the definitions of the perceived ease-of-use and usefulness. Finally, the pre-tested indicators were validated in two empirical studies. In the first study, a sample of 112 users participated within the IBM Canada's Toronto Development Laboratory to evaluate the ease-of-use and usefulness of two systems available over there.

The results of this study indicated that six indicators are adequate for each of the metrics to obtain reliability levels above 0.9. Thus, the indicators were refined and the remaining indicators were validated in the second study. In study 2, 40 evening MBA students at Boston University participated to evaluate two IBM PC-based graphics systems. The results of the Cronbach’s alpha in the second study indicated 0.98 and 0.94 for perceived usefulness and ease-of-use, respectively.

Herein, the user survey (Appendix E) was modified to focus the indicators (Table 20) evaluated by study participants on the MaPS Sustainability Analysis Tool.

Table 20. TAM metrics: Ease-of-use (E) and usefulness (U)

Indicator	Description
E1	Using the MaPS tool in my job would enable me to accomplish tasks more quickly
E2	Using the MaPS tool would improve my job performance
E3	Using the MaPS tool in my job would increase my productivity
E4	Using the MaPS tool would enhance my effectiveness on the job
E5	Using the MaPS tool would make it easier to do my job
E6	I would find the MaPS tool useful in my job
U1	Learning to operate the MaPS tool would be easy for me
U2	I would find it easy to get the MaPS tool to do what I want it to do
U3	My interaction with the MaPS tool would be clear and understandable
U4	I would find the MaPS tool to be flexible to interact with
U5	It would be easy for me to become skillful at using the MaPS tool
U6	I would find the MaPS tool easy to use

The metrics of interest were evaluated by asking study participants to express agreement with statements relating to six indicators for each metric. A Likert scale was applied to gather user opinions about the ease-of-use and usefulness of the tool. To assure every opinion of the participants is captured, the odd number of points provides an opportunity for the participants to select a neutral value, when they truly feel neutral about a given indicator [171,172]. An odd number of points creates a midpoint with the neutral value right in the middle, which provides a standard point of comparison when calculating the mean weighted average and eases data interpretation [173]. However, some researchers prefer to have an even number of points to require participants to reflect their positive or negative opinions [174]. Though no agreement has been reached on whether including the neutral value in the Likert scale is best, a seven-point Likert scale (1: very strongly disagree – 7: very strongly agree) is applied herein as it indicates higher reliability than other options [175].

In addition to the indicators, an open-ended question was presented to the study participants for both metrics to capture additional input. Demographics questions were also included to better understand user backgrounds, e.g., their sustainable product design and other work experiences. Participants had an option to consent to their answers being used in this research or not. It should be noted that this study included both research and human subjects, and was reviewed by the OSU Human Research Protection Program and Institutional Review Board to obtain approval prior to commencing recruitment and other study activities.

Three primary groups of users were recruited and participated in the study from April-June 2020. In early April, 12 undergraduate and graduate engineering students were recruited from the MEI 51706 (Additive Manufacturing) course at Tampere University (TAU) in Finland to evaluate the tool. These students were non-experts in sustainability, but were completing product design projects that utilized additive techniques in their manufacture. From the instructor’s perspective, use of the tool would bring awareness of cost, environmental, and social impacts to his students.

In May-June 2020, 15 undergraduate and graduate students conducting research in the Advanced Manufacturing area within the School of Mechanical, Industrial, and

Manufacturing Engineering (MIME) at Oregon State University (OSU) were recruited. These students were working across several process technology domains and did not have specialized knowledge in comprehensive sustainability assessment. Several of these students were either individually studying manufacturing cost or specific environmental impacts (e.g., energy use) in connection with technology development.

In addition, in Spring 2020, one undergraduate engineering student from MFGE 336 (Production Engineering) and five students in ME 413 (Computer-Aided Design and Manufacturing) participated at OSU, while one OSU student from MFGE 337 (Materials and Manufacturing Processes) tested the tool in Summer 2020. Similar to the students from TAU, OSU students were not experts in sustainability assessment, nor in product design or process analysis. They were engaged in learning core concepts in these domains, and would not otherwise have had the opportunity to explore the connections between product/process sustainability performance and the primary topics covered in these courses.

In sum, 24 students consented to be part of this study, which involved completion of a set of learning activities, including use of the tool as well as the user survey. The construction of the learning activities including the tutorial of the MaPS Sustainability Analysis Tool and the activity description is discussed in the next section.

5.2 Construction of the Learning Activities

To aid in evaluating the operational performance of the tool in terms of ease-of-use and usefulness, a learning module was developed to guide the students in working with the tool. The learning outcomes of the study are described as follows:

- Analyze the impacts of product architecture, manufacturing process, and supply chain decisions on the economic, environmental, and social sustainability of a product.
- Articulate the impacts of product architecture, manufacturing process, and supply chain decisions on the economic, environmental, and social sustainability of a product.
- Construct product design solutions that address technical requirements, in addition to economic, environmental, and social sustainability goals.

Students interacted with the tool using supporting materials outside of class and lab time without the input of their instructor. The supporting materials included a tutorial (Appendix F) and a step-by-step activity description (Appendix G). The tutorial introduces the MaPS Sustainability Analysis Tool and provides an example case study to quantify the sustainability performance of a plastic product. In the activity description, the activities required to conduct the assessment and improve sustainability performance for a product were provided, in addition to a link to the survey.

To analyze the part using the MaPS Sustainability Analysis Tool, users need the information described in the tutorial and product geometry data from a CAD file. Thus, to facilitate accessibility, a CAD file for a hexacopter (Figure 34) was included with the learning module files. However, students could use any CAD file to investigate the sustainability performance of any desired product. For example, some the students in MEI 51706 and ME 413 used a product they had designed previously for assignments in their courses.

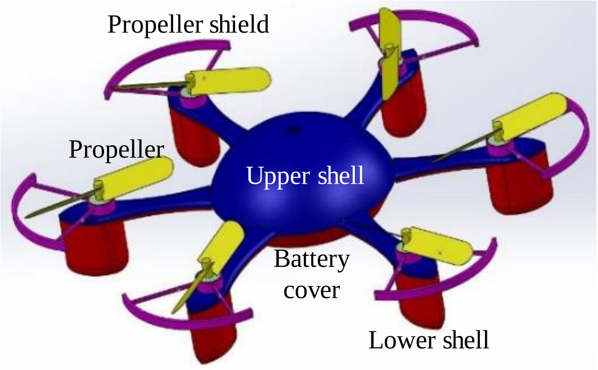


Figure 34. Solid model of the hexacopter

As reported in Chapter 4, the MaPS Sustainability Analysis Tool was developed in MS Excel to enable non-experts to conduct sustainability assessment. The tool has four modules and each module includes two main sections: *information* and *analysis*. Thus, the MaPS Sustainability Analysis Tool utilizes several information resources to support sustainability assessment. To improve usability of the MaPS Sustainability Analysis Tool, these information resources are integrated as described below.

First, the numerical unit manufacturing process and supply chain models to quantify the economic, environmental, and social performance metrics were reviewed to identify the key parameters and the variables in each model. While users are supposed to provide values for the key variables of the models in the MaPS tool *analysis* section of the tool, the key parameters of the numerical models should be provided for them. This enables them to create and to analyze different manufacturing and supply chain scenarios considering sustainability performance.

Second, the existing product design, supply chain configuration, and manufacturing process information resources were reviewed to identify the information provided from each resource (e.g., raw material, product dimensions, distances between locations, transportation time, speed and capacity of the selected transportation mode, and manufacturing process cycle time). The information from these resources provide inputs for the key parameters of the numerical unit manufacturing process and supply chain models.

Third, the key product design, supply chain, and manufacturing process information from the *information* section of the tool was identified and connected to the key parameters of the numerical models in the *analysis* section of the tool. This was accomplished by ensuring the numerical formulations (transformation equations) utilize the data contained in the *information* resources as model inputs for the key parameters of the numerical models in the *analysis* section of the tool.

Finally, in addition to the information resources, the numerical model developed for the metal injection molding process (presented in Chapter 4) was integrated into the tool in connection with the previous three activities. First, the key parameters and the variables of the metal injection molding process were identified. Next, the information resource for the metal injection molding was to identify the key information required for the key parameters of the model. Finally, the key information identified from the *information* section of the tool was connected to the key parameters of the numerical model in the *analysis* section of the tool. A manuscript describing the model is submitted to the *Journal of Production Engineering – Research & Development* [49].

5.3 Results and Analysis

For each indicator in the survey noted above, results were statistically analyzed to evaluate feedback from the participants. Demographic information for the participants are presented in Section 5.3.1. The results of the perceived ease-of-use and usefulness evaluation are discussed in Sections 5.3.2 and 5.3.3, respectively.

5.3.1 Study Participant Demographics

As mentioned above, undergraduate and graduate engineering students were recruited for this study from Tampere University (TAU), Tampere, Finland, and Oregon State University (OSU), Corvallis, Oregon, USA. Demographics of the participants from both universities are summarized in Figure 35. Overall, 42% and 58% of the participants were undergraduate and graduate students, respectively. Among the undergraduate students, nine students were seniors and one was a junior. Of the students pursuing graduate degrees, six were doctoral students and the remaining eight were masters students.

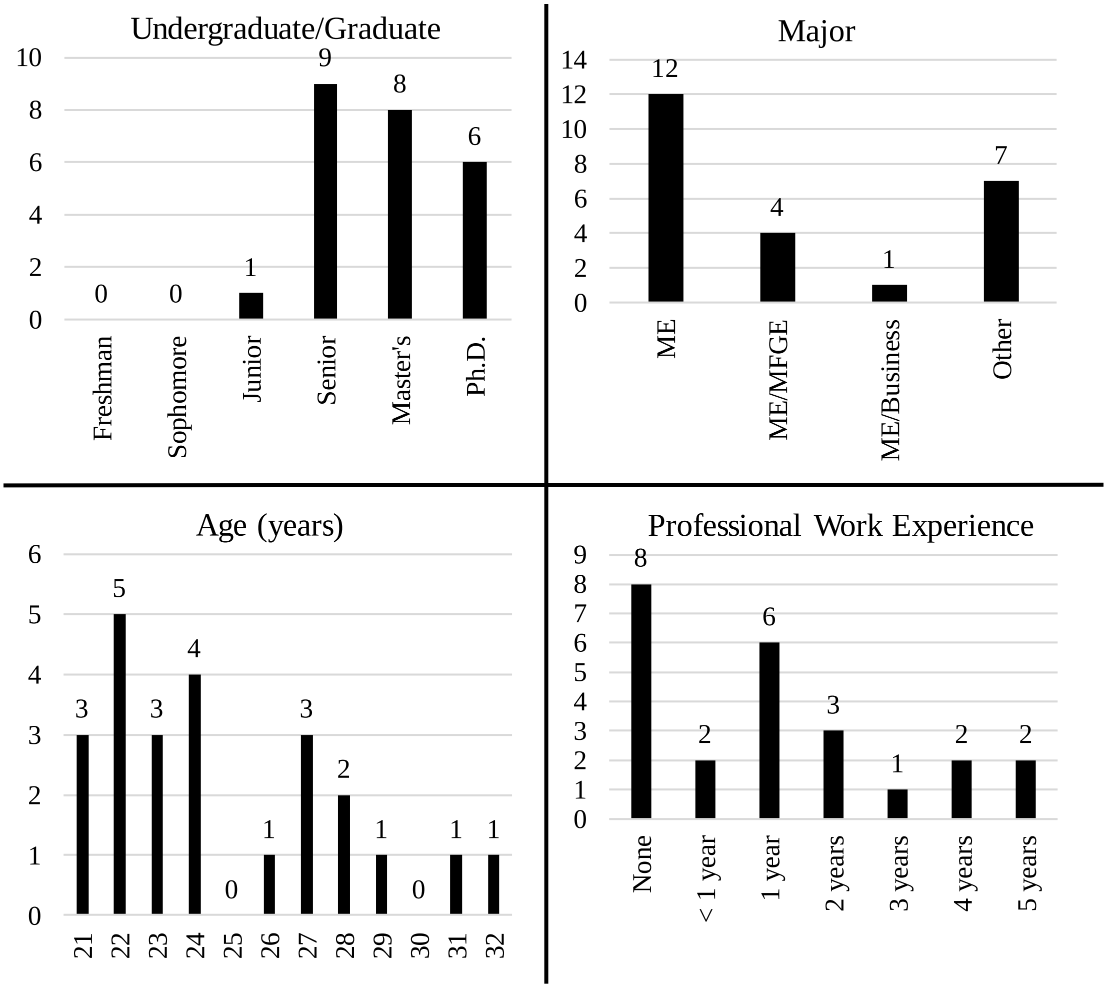


Figure 35. Demographics of the participants evaluating the MaPS tool

Half of the students were majoring in Mechanical Engineering (ME), while two at OSU were pursuing individual degrees in Industrial Engineering (IE) and Manufacturing Engineering (MFGE). Four OSU students were double majoring in Mechanical Engineering and Manufacturing Engineering (ME/MFGE). Two OSU students were pursing majors in Computer Science and Robotics. At TAU, one student was majoring in Mechanical Engineering and Business Administration, and three were pursuing various domains of Automation Engineering.

The participants were distributed between the ages of 21-32 years, with an average age of 25 (the median age and standard deviation were 24 and 3.16, respectively). All but one of the participants were male. Two thirds of the participants had some level of professional work experience. Of those with work experience, two students had one year or less, nine students had 1-2 years, and five students 2-5 years of work experience. Demographics questions provides better understanding about the users' backgrounds and their experiences in sustainable product design.

5.3.2 Perceived Ease-of-use

The statistical analysis of indicator results for the perceived ease-of-use metric is presented in Table 21. The median for indicators E1, E2, and E5 is 6 (strongly agree), and for the remaining indicators is 5 (agree). For the indicator E1, 83% of the participants (20 students) selected 5 and above and found it easy for themselves to learn to operate with the MaPS tool. Among them, 60% (12 participants) selected 6 (strongly agree) for this indicator. In addition, 92% of the participants (22 students) found it easy to get the MaPS tool to do what they wanted it to do (E2), selecting 5 (agree) and above. Eleven students from this group strongly agreed with indicator E2. Nearly 80% of the participants (19 students) found the tool clear and understandable (E3), with the majority (nine students) selecting 5 (agree) in the survey, while seven selected 6 (strongly agree) and three selected 7 (very strongly agree).

For the fourth indicator (E4), 58% of the participants (14 students) found the tool to be flexible to interact with and selected 5 (10 students) and 6 (four students). Around 30%

of the participants (seven students) indicated that they neither agreed nor disagreed with this indicator. Twenty students (83% of the participants) found it easy to become skillful at using the tool (E5) and selected 5 (agree) and above. Interestingly, the frequency of the responses for this indicator is highly skewed to the right and eight students (34%) selected 7 (very strongly agree), 7 students (29%) selected 6 (strongly agree), and 5 students (21%) selected 5 (agree). Finally, 83% of the participants (20 students) found the tool easy to use and selected 5 and above. Among these participants, the majority (45%, nine students) selected 5 (agree), seven students (29%) selected 6 (strongly agree), and four students (17%) selected 7 (very strongly agree).

Table 21. Summary of the analysis for perceived ease-of-use indicators

Metric	Description	Median	Mean	Std. Dev.
E1	Learning to operate the MaPS tool would be easy for me	6	5.46	0.957
E2	I would find it easy to get the MaPS tool to do what I want it to do	6	5.54	0.999
E3	My interaction with the MaPS tool would be clear and understandable	5	5.21	1.154
E4	I would find the MaPS tool to be flexible to interact with	5	4.63	0.904
E5	It would be easy for me to become skillful at using the MaPS tool	6	5.75	1.164
E6	I would find the MaPS tool easy to use	5	5.42	1.037

It should be noted that none of the participants selected 1 (very strongly disagree) or 2 (strongly disagree) for any of the indicators under the ease-of-use metric. Overall, four graduate engineering students at TAU and one undergraduate engineering student at OSU selected 3 (disagree) for several ease-of-use indicators. One student at TAU selected 3 (disagree) for indicators E1-E4 without providing further comments. However, this student found the tool easy to use and selected 5 (agree) for indicator

E6. The main reasons provided by the students at TAU for selecting 3 (disagree) were related to problems in providing the required parameters, not understanding the flow of information, and errors in the transportation calculations. The undergraduate student at OSU selected 3 (disagree) for indicators E2, E4, and E6. This student had difficulty in tracking down the information in the tool. The frequencies of individual responses for the perceived ease-of-use metric indicators are presented in Figure 36.

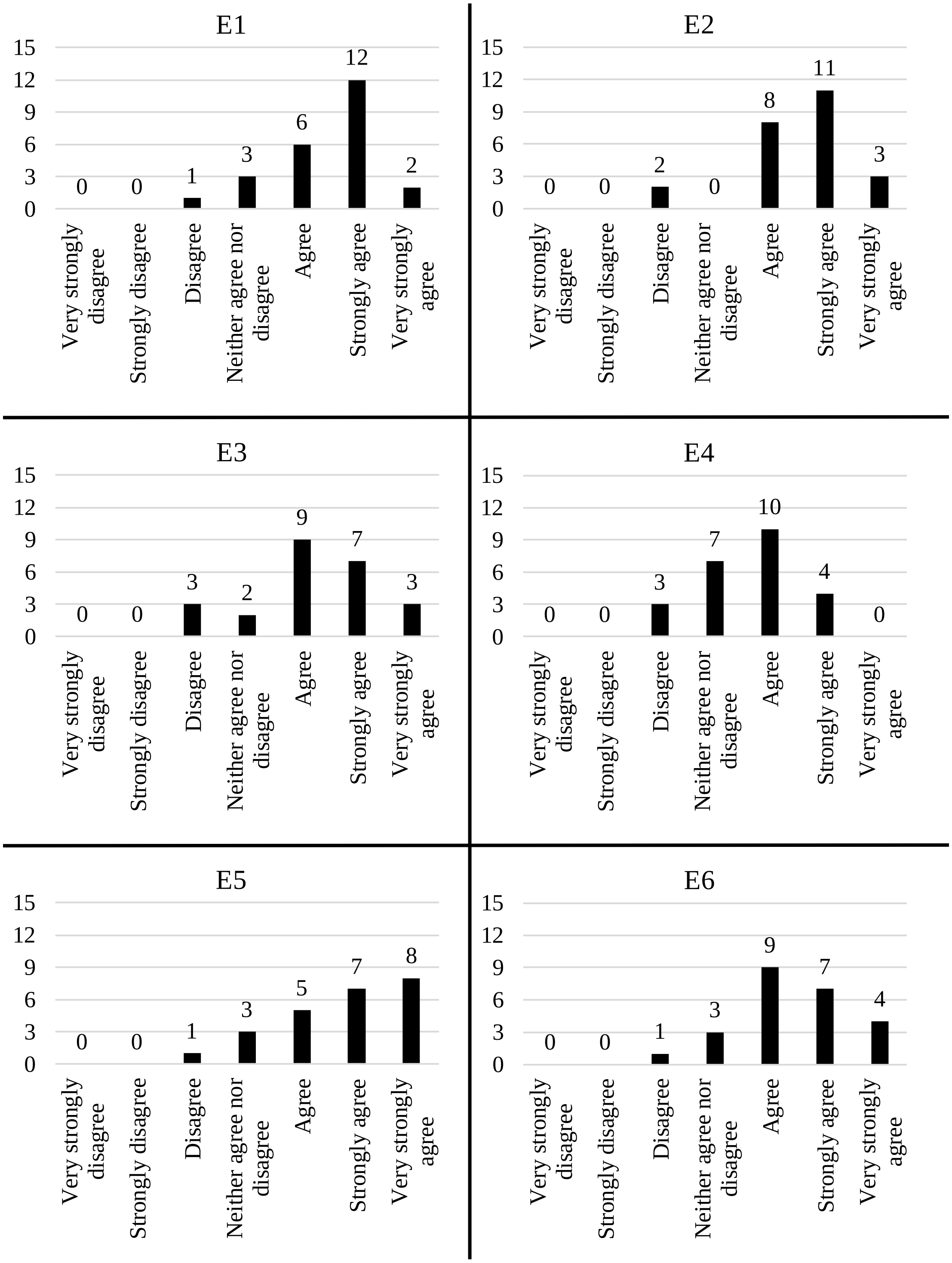


Figure 36. Frequency of the responses for perceived ease-of-use indicators

5.3.3 Perceived Usefulness

The statistical analysis of the results for the perceived usefulness metric is presented in Table 22. The median for each of the indicators is 5 (agree), with the responses largely following the trend of a normal distribution, centered on or greater than 5 (agree). This indicates that the participants were generally favorable that the tool was useful. Several of the indicators (i.e., U3, U4, and U6) were viewed more positively overall. The frequency of responses for each of the perceived ease-of-use indicators is presented in Figure 35.

Table 22. Summary of the analysis for perceived usefulness indicators

Metric	Description	Median	Mean	Std. Dev.
U1	Using the MaPS tool in my job would enable me to accomplish tasks more quickly	5	5.00	1.258
U2	Using the MaPS tool would improve my job performance	5	5.00	0.866
U3	Using the MaPS tool in my job would increase my productivity	5	5.21	1.117
U4	Using the MaPS tool would enhance my effectiveness on the job	5	5.29	0.934
U5	Using the MaPS tool would make it easier to do my job	5	5.04	0.889
U6	I would find the MaPS tool useful in my job	5	5.21	1.079

Nearly two thirds of the participants (15 students) indicated that using the tool would enable them to accomplish tasks more quickly (U1). The majority of them (seven students) selected 5 (agree), while four selected 6 (strongly agree) and four selected 7 (very strongly agree). For the second indicator (U2), 75% of the participants (18 students) noted that using the tool would improve their performance; 12 students selected 5 (agree). With regard to the productivity (U3), 71% of the participants (17 students) thought that using the tool would increase their productivity. Similar to the previous indicators, participants selected 5 (agree) with the highest frequency (eight students).

For the fourth indicator (U4), 83% of the participants (20 students) found using the tool would enhance their effectiveness on the job, and selected 5 and above. The majority of students selected strongly agree (10 students) and very strongly agree (eight students) for this indicator. Three quarters of the participants (18 students) found using the tool would make it easier for them to do their job and selected 5 and above. Among them, 11 students selected 5 (agree) and six students selected 6 (strongly agree). Finally, 71% of the participants (17 students) indicated that they would find the tool useful in their job, selected 5 (agree) and above. Fourteen students selected 5 (agree) and 6 (strongly agree) equally, with three students selecting 7 (very strongly agree).

It should be noted that similar to the ease-of-use metric, none of the participants selected 1 (very strongly disagree) and 2 (strongly disagree) for any of the indicators under the usefulness metric. The graduate student from TAU who disagreed with indicators E1-E4 for the ease-of-use metric disagreed with usefulness indicator U1, but did not provide additional comments. This student strongly agreed that the tool was useful (indicator U6). The other graduate student from TAU selected 3 (disagree) for all the indicators (U1-U6) under this metric. This student commented, “[I]n most companies the sustainability is not in the focus when selecting a supplier or manufacturing method.”

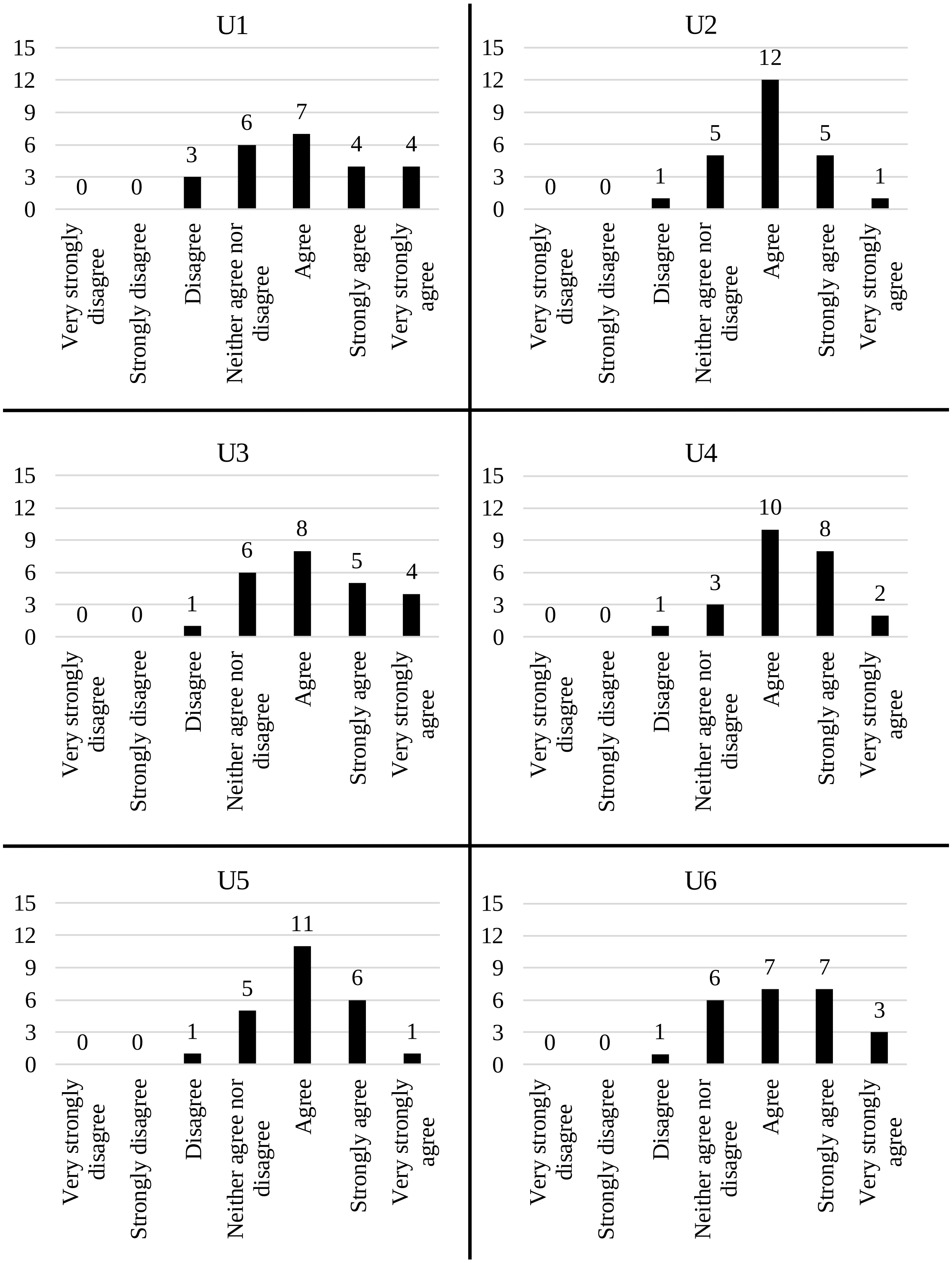


Figure 37. Frequency of the responses for the perceived usefulness metric

The undergraduate engineering student from OSU who disagreed with three ease-of-use indicators (i.e., E2, E4, and E6) also disagreed with usefulness indicator U1, which relates to how quickly a task can be accomplished using the tool. They stated that they could not comment adequately about the tool's usefulness since they were not evaluating a real-world scenario, and felt that "REAL WORLD TESTING" was necessary, rather than seeking input from students. This student also selected 4 (neither agree or disagree) for U2, U3, U5, and U6, but selected 5 (agree) for U4, which related to on-the-job effectiveness.

5.4 Discussion of Results

From the foregoing analysis, the operational performance of the MaPS Sustainability Analysis Tool can be evaluated in terms of the ease-of-use and usefulness metrics. The tool was used by 24 undergraduate and graduate engineering students from Tampere University, Finland and Oregon State University, United States in completing specified learning activities. The students were between 21 and 32 years old and were studying industrial, manufacturing, and mechanical engineering, or related fields. Only one student participant was female and only four of the participants had more than four years of work experience. The statistical analysis of their responses found the median of each of the indicators for both metrics were 5 (agree) or 6 (strongly agree). In addition, the mean values of responses ranged from 4.63-5.75 – with only indicator E4, relating to the tool's flexibility, falling under 5.

This analysis shows that the participants who evaluated the MaPS Sustainability Analysis Tool found it easy-to-use and agreed that it would be useful in the task of analyzing the product design, supply chain, and manufacturing process sustainability performance (i.e., environmental, economic, and social impacts). However, it was also clear that the tool's flexibility needs to be improved, which would require moving beyond a proof-of-concept to a more functional and usable software tool [176]. *Software functionality* relates to the ability of the tool to provide the user with the functions needed to perform their tasks [177], while *software usability* refers to the efficiency, effectiveness, satisfaction, and learnability of the tool [178].

As mentioned above, the proof-of-concept MaPS Sustainability Analysis Tool applies the unit manufacturing process (UMP) modeling approach to quantify the sustainability performance of different manufacturing processes and systems in terms of economic, environmental, and social impact metrics. Currently, all the numerical models are implemented as spreadsheet models (MS Excel) in the tool, as discussed in detail in Chapter 4. Thus, the necessary advancement to enhanced functionality and usability would require significant model development and interface development, and would enable users to evaluate a range of material, product, process, and supply chain options. While this would be a significant undertaking, requiring a software development team, a number of opportunities were identified to improve the user study as well as the operational performance of the tool, as summarized in the following sections.

5.4.1 Opportunities for User Study Improvement

While conducting the user studies and evaluating the study results, several areas of improvement were noted. Although the results obtained allowed conclusions to be drawn about operational performance of the existing proof-of-concept tool, modifications to the study methods would ensure consistency of responses, clarify the intension of the study purpose, and involve broader user communities.

First, it was found that survey wording may have led to some confusion. For example, from the comments reported above, the use of “job” was interpreted by one participant as a working in a real-world industry. The student didn’t see the connection of the tool being used in the learning setting as a “job” environment. This terminology could be rephrased to indicate the task of conducting sustainability performance assessment as the “job” to be completed. Thus, to avoid confusion, “job” in all the survey indicators could be replaced with “design project,” for instance.

Although ME 413, MFGE 336, and MFGE 337 have large enrollments, the total number of participants was less than 10% for each class recruited. To increase the number of participants, the study could be added as an extra-credit assignment and/or more time could be given to complete the activity. In addition, to recruit more students, additional reminders could be sent, class or lab time could be set aside and devoted to the activity, or a more generous form of compensation could be offered (higher points or higher monetary rewards – a $15 gift card was given to OSU participants).

Finally, it was noted that only one female user participated in this study. Diverse problem-solving styles within a gender as well as between one gender and another result in diverse interpretation and analysis (e.g., different levels of risk tolerance and information processing style) of different subjects [179,180]. To confirm the MaPS Sustainability Analysis Tool functions in a manner that is inclusive for all users, a diverse set of participants should be recruited to provide their opinions and feedback about the tool's ease-of-use, usability, and other characteristics [181].

5.4.2 Improving Software Functionality and Usability

As noted above, study participants found the limited flexibility of the tool as its largest deficiency, with the mean of responses falling less than 5 (agree). Several steps can be taken to improve the functionality of the software. In particular, a more formalized software development process could be undertaken [182]. A number of software design paradigms have been developed and implemented. These all take care to carefully define operational characteristics, with newer approaches often applying agile, iterative techniques (e.g., Scrum) to ensure user needs are well-defined and attended to the result tool. In so doing, the key software tool attributes of *efficiency*, *effectiveness*, *satisfaction*, and *learnability* are brought closely into focus of the whole team [178].

For example, the *efficiency* of use of the tool could be improved by implementing the functions in a dedicated software tool. To achieve this, alternative programming languages Java, JavaScript, and Python could be considered to construct the tool [183]. Considering their capabilities, such as portability, existing web frameworks/libraries, web service security, and built-in graphical user interfaces (GUIs), they can provide a platform for a tool developer to improve the tool's flexibility, which would also contribute to higher efficiency [184,185].

In addition to the tool's efficiency, a more flexible tool with a broader set of features (e.g., a more user-friendly GUI) would greatly improve the *learnability* [186–188], or relative ease with which a user can learn how to use the new tool. Moreover, a more sophisticated GUI would improve the *effectiveness* of the tool, as well as the *satisfaction* of the user as they interact with the tool to analyze their product [189,190]. For example, representation of the myriad quantitative results from sustainability assessment can be improved by applying data visualization techniques, such as bubble charts and treemaps [191]. Improved data visualization enables non-expert decision makers to have a better understanding about the quantitative sustainability assessment results and to assist them in evaluating sustainability performance of the intended product [47,192,193].

Currently, different UMPs are included in the MaPS Sustainability Analysis Tool to investigate the sustainability performance of making products from plastics and metals using a subset of additive and subtractive manufacturing processes. To improve the effectiveness of the tool, more UMP models could be adopted from the existing literature and added to the tool. Moreover, new numerical models could be developed for different processes and be added to the tool. This added functionality would equip students and industry users with additional flexibility in assessing products of their own design, especially products that utilize different and varied materials and geometries in their designs. These product designs would likely require more complex supply chains, which would also necessitate added supply chain modeling and analysis functionality.

Chapter 6: SUMMARY AND CONCLUSIONS

The purpose of Chapter 6 is to present the features of this research as well as a summary of the completed research tasks. Moreover, conclusions and contributions of this research as well as the future research directions are discussed in this chapter.

6.1 Research Overview

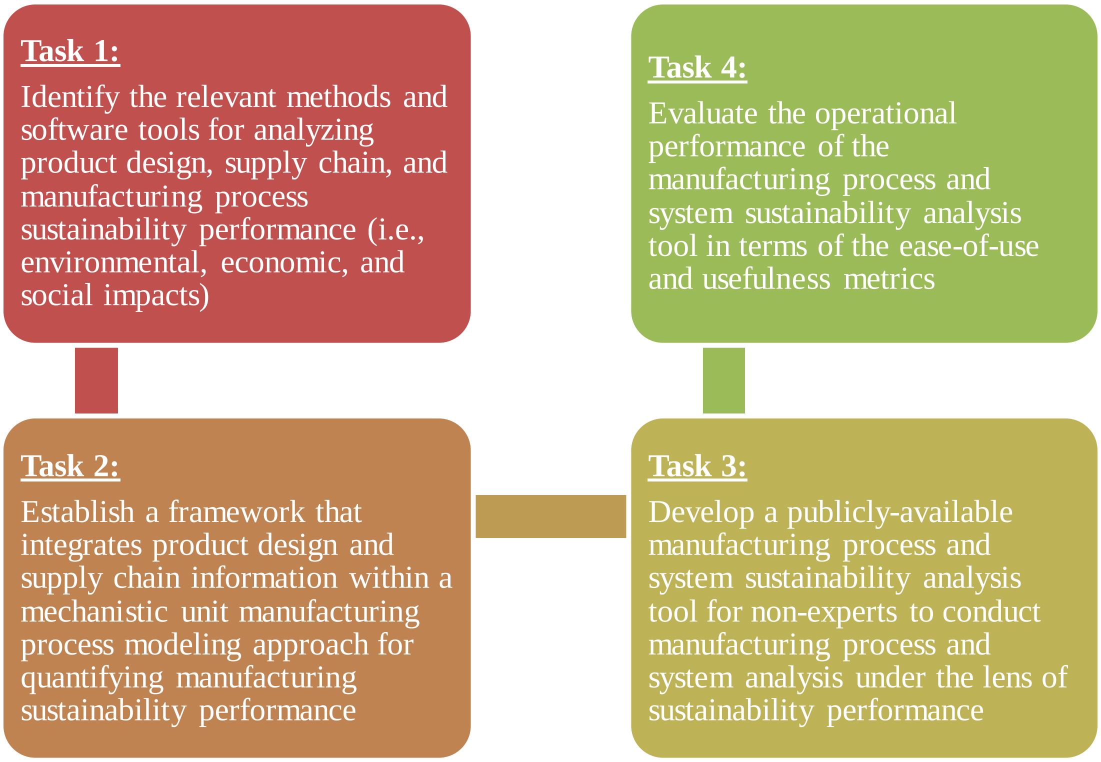
Ultimately, the research presented in this dissertation is essential to overcome challenges in sustainable manufacturing process and system analysis faced by non-experts. The deficiencies of existing sustainability assessment methods, discussed in Chapter 2, include a focus on only one or two of the three pillars of sustainability during product design as well as the application of *ad hoc* sustainable product design and manufacturing methods. From the literature review presented in Chapter 2, it was found that a myriad of methods has been developed for experts to evaluate economic and environmental performance of manufacturing processes during product design. In addition to these methods, a number of environmental impact assessment tools, e.g., Granta CES EduPack [4], SolidWorks Sustainability [5], Sustainable Minds [6], OpenLCA [7], IDEMAT [8], SimaPro [9], and GaBi [10], as well as several CAD-integrated LCA tools [11–13], have been developed.

A prior review of these and other eco-design tools found that they focus on environmental impacts and require users to have domain knowledge [14], which inhibits the utility of these tools in supporting non-experts in sustainable design. Further, dedicated LCA tools require highly detailed unit process data and information for accurately estimating environmental impacts, adding to their human resource-intensity [1]. CAD-integrated LCA tools rely on a simplifying mass-based approach, which does not allow high-fidelity analysis of product geometry-related impacts of unit manufacturing processes and supply chains [38,111,113].

The identified problem addressed by this research is the lack of a unit manufacturing process model-based approach to assist non-expert decision makers in quantifying and evaluating the impacts of product design changes on the sustainability performance of manufacturing processes and systems. The research pursues the hypothesis that implementation of standards-based unit manufacturing process models within an easy-to-use, publicly-available manufacturing process and system sustainability analysis tool will enable sustainability performance assessment of manufacturing processes and systems. The modeling approach is based on the method for manufacturing process characterization specified by ASTM E3012-20, Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes [83].

6.2 Summary of Research Tasks

This research has the objective of facilitating the simultaneous analysis of sustainability performance (i.e., environmental, economic, and social impacts) of different manufacturing processes and systems through unit manufacturing process modeling within an easy-to-use, publicly-available manufacturing process and system sustainability analysis tool [48,50]. To fulfill the research objective, four main tasks detailed below were undertaken in the research presented herein (Figure 38).



Task 1:
Identify the relevant methods and software tools for analyzing product design, supply chain, and manufacturing process sustainability performance (i.e., environmental, economic, and social impacts)

Task 2:
Establish a framework that integrates product design and supply chain information within a mechanistic unit manufacturing process modeling approach for quantifying manufacturing sustainability performance

Task 3:
Develop a publicly-available manufacturing process and system sustainability analysis tool for non-experts to conduct manufacturing process and system analysis under the lens of sustainability performance

Task 4:
Evaluate the operational performance of the manufacturing process and system sustainability analysis tool in terms of the ease-of-use and usefulness metrics

Figure 38. Research tasks

6.3 Conclusions

First, from a review of the literature, it was found that while methodologies and tools have been developed for experts to evaluate sustainability performance metrics for manufacturing processes during product design phase, they remain ill-suited for educating non-expert decision makers about sustainable engineering for several reasons: (1) relating sustainability information to the product conceptual design is challenging for non-experts; (2) the eco-design software tools often require costly licensing and are not easy to access; (3) domain expertise (knowledge of eco-design issues and tools) and extended analysis times are required to produce meaningful results; and (4) software tools are needed which are simple and user-friendly.

Second, while much recent work has been done, a critical deficiency in the ability of life cycle assessment software tools to perform manufacturing process-level analysis, identified in literature over the past two decades, was found to be yet present. Since these tools rely on product mass to quantify manufacturing processes environmental impacts, it is difficult to effectively investigate the impacts of product design changes on processes, especially when product mass or process parameters experience little to no change. Thus, non-experts are especially challenged in conducting accurate manufacturing stage environmental impact assessment. Thus, the framework and tool emerging from this dissertation applies manufacturing-process level assessment using the unit manufacturing process modeling approach for environmental impacts and the manufacturing process design approach for cost analysis.

Third, while much effort has been invested in identifying and quantifying various metrics for conducting sustainability impact assessment, it was found that many analysis approaches remain focused on individual aspects of sustainability. For example, most methods and software tools quantify environmental impacts, often connected with cost analysis, and social impact analysis is less frequent. In addition, comprehensive quantitative sustainability impact assessment during the product design phase, where all the three pillars of sustainability are investigated, remains a deficiency in reported sustainability performance assessment studies, methods, and tools. Thus, a framework was needed to facilitate the simultaneous analysis of sustainability performance for manufacturing processes and systems during product design phase. This dissertation research develops and presents a sustainability performance assessment framework extending from the theoretical basis of unit manufacturing process modeling, but also incorporating design and analysis methods from product development and supply chain configuration research.

Fourth, in evaluating the operational performance of the MaPS Sustainability Analysis Tool by surveying a number of undergraduate and graduate engineering students across different programs, program levels and universities, it was found that this proof-of-concept tool was perceived to be easy to use and useful in completing sustainability assessment tasks. In fact, the median responses showed agreement with all the standard indicators evaluated using the Technology Acceptance Model (TAM). At the same time, a number of opportunities for improvement were noted based on the experience of administering the study and analyzing student feedback, as discussed in Chapter 5.

6.4 Contributions

The work reported herein is comprehensively presented in order to enable future replication and expansion of the framework, methods, and model developed, as well as enabling future evaluation of the development, implantation, and analysis of the MaPS Sustainability Analysis Tool. The contributions of this dissertation research to the literature are summarized in Table 1 presented in Section 1.8, and summarized below.

First, to support the sustainability impact assessment, four new metrics for evaluating social impact were developed: 1) nonfatal injuries and illnesses and 2) days away from work relative to transportation activities and manufacturing processes. They are quantified using data available for various industry sectors from the U.S. Bureau of Labor Statistics, based on the time engaged in working. These metrics enable industry and academia to quantify the level of safety in the work environment.

Second, to address the need of a framework for educating non-expert decision makers about sustainable engineering, a sustainability performance assessment framework was developed herein. The framework is based on the theoretical basis of unit manufacturing process modeling and is comprised of four phases: Product Development, Supply Chain Configuration, Manufacturing Process Design, and MaPS Sustainability Analysis. The framework can facilitate the simultaneous analysis of sustainability performance for manufacturing processes and systems from cradle-to-gate life cycle scope by non-expert decision makers. For example, it can be used in the classroom and laboratory settings for sustainable product design and manufacturing.

Third, to address the barriers of existing sustainability assessment methods and tools identified in the literature, a publicly-available, proof-of-concept software tool (MaPS Sustainability Analysis Tool) for non-expert manufacturing process and system analysis has been developed in MS Excel [50] and deployed in several undergraduate engineering lab settings, and evaluated by undergraduate and graduate engineering students at two institutions. The tool incorporates UMP models to eliminate the need for detailed process data and has four modules: *Part Specification*, *Supply Chain Configuration*, *Manufacturing Process*, and *MaPS Sustainability Analysis*. Each module includes two main sections: *information* and *analysis*. The *information* section captures the inputs from a user and the *analysis* section provides the sustainability assessment results. MaPS Sustainability Analysis Tool was found to be easy-to-use, which can be an advantage over costly eco-design software tools. Moreover, it was found to be useful, enabling non-expert decision makers to perform manufacturing cost and productivity assessment, in addition to the social and environmental impact analyses, based on the product design (i.e., part geometry and material information).

Fourth, in addition to unit manufacturing process models adopted from the literature, a unit manufacturing process model was developed for a conventional powder metallurgy process (metal injection molding). The model was implemented in the MaPS Sustainability Analysis Tool by applying the manufacturing process design method. The model developed can be reused by industry and academia for evaluating the production of various products with a range of machines and materials. Moreover, the model can be utilized with other process models to generate life cycle inventory data to support life cycle assessment for an entire flow of unit manufacturing processes in the production of a given product.

6.5 Opportunities for Future Work

To build upon the research presented in the foregoing, the following future directions have been identified.

As mentioned above, the product sustainability assessment framework developed herein is limited to the product cradle-to-gate life cycle scope. To expand the framework, the other phase(s) of the product life cycle should be included. To achieve this, first, all the steps in the use phase and the end-of-life phase should be identified. Next, a systematic literature review should be conducted to identify the existing metrics for quantifying the economic, environmental, and social impacts of the use and end-of-life phases. In addition to applying the identified metrics, the review provides opportunity to develop new metrics. Next, the numerical models should be developed for the steps in each phase and be added to the MaPS Sustainability Analysis Tool, as described in Section 5.2. Then, the required information to analyze the sustainability performance of the phases should be identified. Finally, the *information* and *analysis* sections should be added to the MaPS Sustainability Analysis Tool.

A proof-of-concept MaPS Sustainability Analysis Tool was developed herein to demonstrate the application of the framework for non-expert decision makers. However, the functionality of the MaPS Sustainability Analysis tool should be improved as discussed in Section 5.4.2. First, the operational performance of the software tools should be defined to ensure the MaPS Sustainability Analysis Tool functions in a manner that is inclusive for all users. This can be achieved by recruiting a diverse set of participants to provide their opinions and feedback about a tool's operational characteristics and graphical user interface (GUI). In addition, key software tool attributes of *efficiency*, *effectiveness*, *satisfaction*, and *learnability* should be investigated to improve the functionality of the MaPS Sustainability Analysis Tool. Second, different programming languages should be reviewed to compare their relative advantages and to identify their capabilities. Next, using the selected programming language, a dedicated software tool should be developed to implement the functions of the MaPS Sustainability Analysis Tool to improve the *efficiency*. This will result in improving the tool's flexibility, which would contribute to higher efficiency.

In addition to the *efficiency*, another tool attributes (*learnability*) can be improved by a more flexible tool. This can be achieved by having a more user-friendly GUI, which shortens the learning curve of a user to work with the tool. Moreover, user understanding and interpretation of the sustainability analysis results is significantly influenced by data visualization techniques applied in the GUI. In addition to the *efficiency*, a more flexible tool with a broader set of features (e.g., a more user-friendly GUI) can improve the *satisfaction* of the users while conducting sustainability impact assessment of the intended product.

The proof-of-concept MaPS Sustainability Analysis Tool has different additive and subtractive unit manufacturing processes (UMPs) for making plastic and metal products. To improve the *effectiveness* of the MaPS Sustainability Analysis Tool, more UMP numerical models could be adopted from the existing literature and added to the tool as described in Section 5.2. First, the key parameters and variables in the model to quantify the economic, environmental, and social performance metrics should be identified. Second, the *information* sections in each module of the MaPS Sustainability Analysis Tool should be reviewed to approve the required inputs for the key parameters are available. Third, by using numerical formulations (transformation equations), the data contained in the *information* sections should be connected to the key parameters of the numerical model in the *analysis* section of the modules. In addition, new numerical models could be developed using data-driven or physics-based approaches for different manufacturing processes and be added to the tool.

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Appendix A: Metal Extrusion UMP Model

Graphical representation of the metal extrusion UMP model, including the transformation equations is presented in Figure 39.

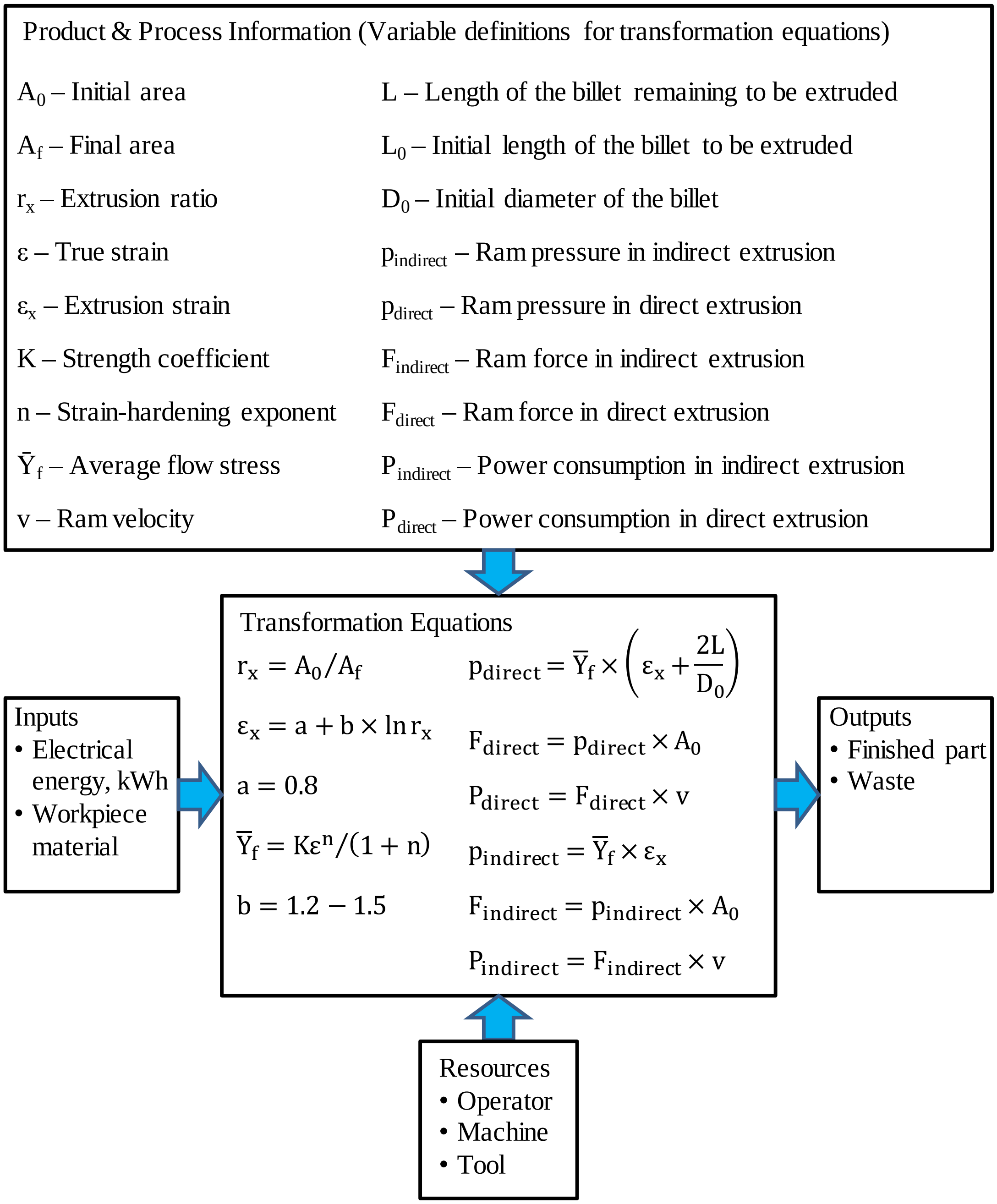


Figure 39. Metal extrusion UMP model (based on [138])

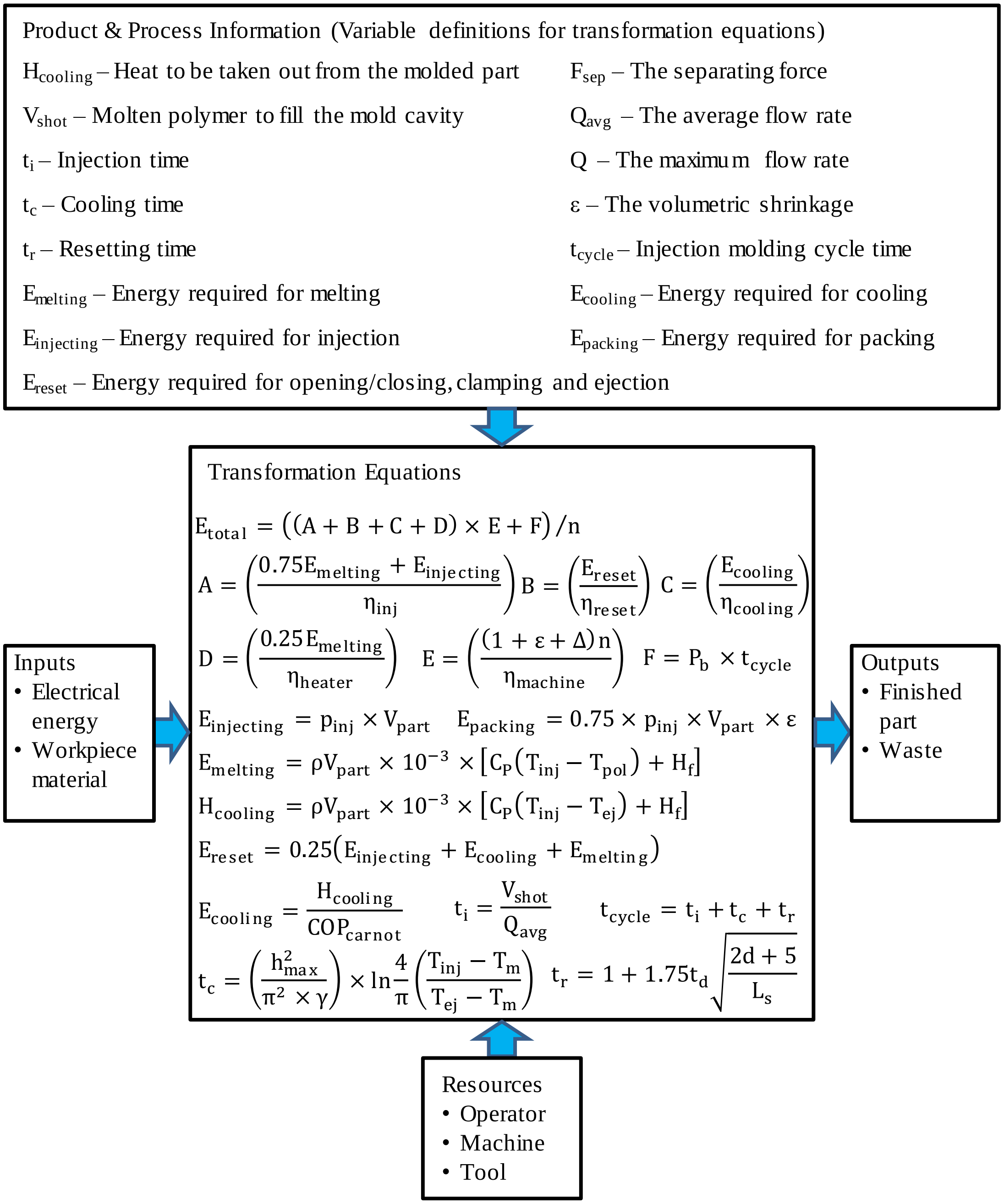
Typical values of strength coefficient (K) and strain hardening exponent (n) for different metals at room temperature, which are used in the transformation equations of the metal extrusion process are presented in Table 23 [138].

Table 23. Strength coefficient and strain hardening exponent for different metals

Material	Strength coefficient, K (MPa)	Strain hardening exponent, n
Aluminum, pure, annealed	175	0.2
Aluminum alloy, annealed	240	0.15
Aluminum alloy, heat treated	400	0.1
Copper, pure, annealed	300	0.5
Copper alloy: brass	700	0.35
Steel, low C, annealed	500	0.25
Steel, high C, annealed	850	0.15
Steel, alloy, annealed	700	0.15
Steel, stainless, austenitic, annealed	1200	0.4

Appendix B: Polymer Injection Molding UMP Model

Graphical representation of the polymer injection molding UMP model, including the transformation equations is presented in Figure 40.



Product & Process Information (Variable definitions for transformation equations)

$H_{cooling}$ – Heat to be taken out from the molded part

V_{shot} – Molten polymer to fill the mold cavity

t_i – Injection time

t_c – Cooling time

t_r – Resetting time

$E_{melting}$ – Energy required for melting

$E_{injecting}$ – Energy required for injection

E_{reset} – Energy required for opening/closing, clamping and ejection

F_{sep} – The separating force

Q_{avg} – The average flow rate

Q – The maximum flow rate

ε – The volumetric shrinkage

t_{cycle} – Injection molding cycle time

$E_{cooling}$ – Energy required for cooling

$E_{packing}$ – Energy required for packing

Transformation Equations

$$E_{total} = \big((A + B + C + D) \times E + F\big)/n$$

$$A = \left(\frac{0.75E_{melting} + E_{injecting}}{\eta_{inj}}\right) B = \left(\frac{E_{reset}}{\eta_{reset}}\right) C = \left(\frac{E_{cooling}}{\eta_{cooling}}\right)$$

$$D = \left(\frac{0.25E_{melting}}{\eta_{heater}}\right) \quad E = \left(\frac{(1 + \varepsilon + \Delta)n}{\eta_{machine}}\right) \quad F = P_b \times t_{cycle}$$

$$E_{injecting} = p_{inj} \times V_{part} \quad E_{packing} = 0.75 \times p_{inj} \times V_{part} \times \varepsilon$$

$$E_{melting} = \rho V_{part} \times 10^{-3} \times \left[C_P\left(T_{inj} - T_{pol}\right) + H_f\right]$$

$$H_{cooling} = \rho V_{part} \times 10^{-3} \times \left[C_P\left(T_{inj} - T_{ej}\right) + H_f\right]$$

$$E_{reset} = 0.25\left(E_{injecting} + E_{cooling} + E_{melting}\right)$$

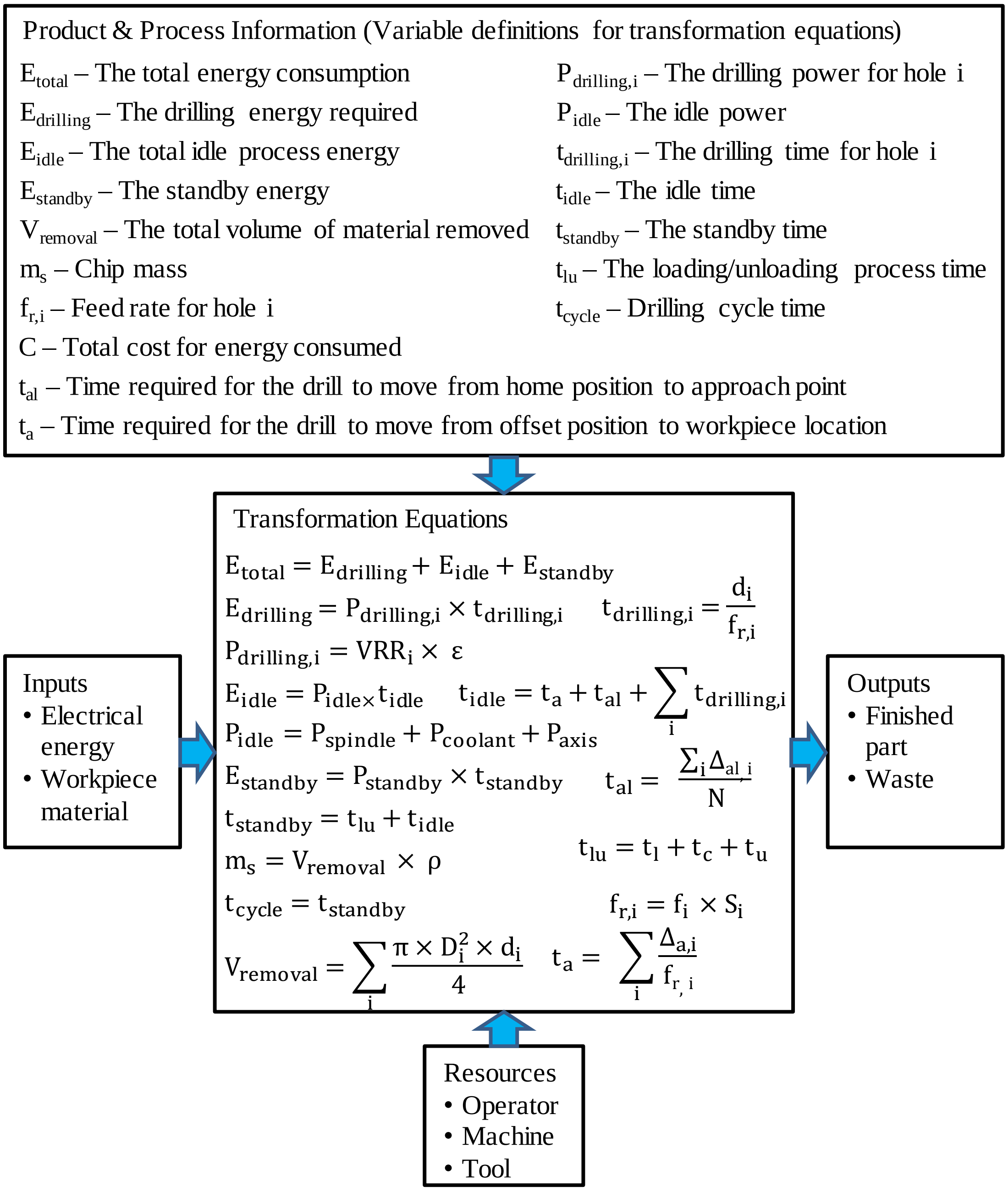
$$E_{cooling} = \frac{H_{cooling}}{COP_{carnot}} \quad t_i = \frac{V_{shot}}{Q_{avg}} \quad t_{cycle} = t_i + t_c + t_r$$

$$t_c = \left(\frac{h_{max}^2}{\pi^2 \times \gamma}\right) \times \ln\frac{4}{\pi}\left(\frac{T_{inj} - T_m}{T_{ej} - T_m}\right) \quad t_r = 1 + 1.75t_d\sqrt{\frac{2d + 5}{L_s}}$$

Figure 40. Polymer injection molding UMP model (based on [76])

Appendix C: Drilling UMP Model

Graphical representation of the drilling UMP model, including the transformation equations is presented in Figure 41.



Product & Process Information (Variable definitions for transformation equations)

E_{total} – The total energy consumption
$E_{drilling}$ – The drilling energy required
E_{idle} – The total idle process energy
$E_{standby}$ – The standby energy
$V_{removal}$ – The total volume of material removed
m_s – Chip mass
$f_{r,i}$ – Feed rate for hole i
C – Total cost for energy consumed
t_{al} – Time required for the drill to move from home position to approach point
t_a – Time required for the drill to move from offset position to workpiece location
$P_{drilling,i}$ – The drilling power for hole i
P_{idle} – The idle power
$t_{drilling,i}$ – The drilling time for hole i
t_{idle} – The idle time
$t_{standby}$ – The standby time
t_{lu} – The loading/unloading process time
t_{cycle} – Drilling cycle time

Inputs
- Electrical energy
- Workpiece material

Transformation Equations

$$E_{total} = E_{drilling} + E_{idle} + E_{standby}$$

$$E_{drilling} = P_{drilling,i} \times t_{drilling,i} \qquad t_{drilling,i} = \frac{d_i}{f_{r,i}}$$

$$P_{drilling,i} = VRR_i \times \varepsilon$$

$$E_{idle} = P_{idle} \times t_{idle} \qquad t_{idle} = t_a + t_{al} + \sum_i t_{drilling,i}$$

$$P_{idle} = P_{spindle} + P_{coolant} + P_{axis}$$

$$E_{standby} = P_{standby} \times t_{standby} \qquad t_{al} = \frac{\sum_i \Delta_{al,i}}{N}$$

$$t_{standby} = t_{lu} + t_{idle}$$

$$t_{lu} = t_l + t_c + t_u$$

$$m_s = V_{removal} \times \rho$$

$$t_{cycle} = t_{standby} \qquad f_{r,i} = f_i \times S_i$$

$$V_{removal} = \sum_i \frac{\pi \times D_i^2 \times d_i}{4} \qquad t_a = \sum_i \frac{\Delta_{a,i}}{f_{r,i}}$$

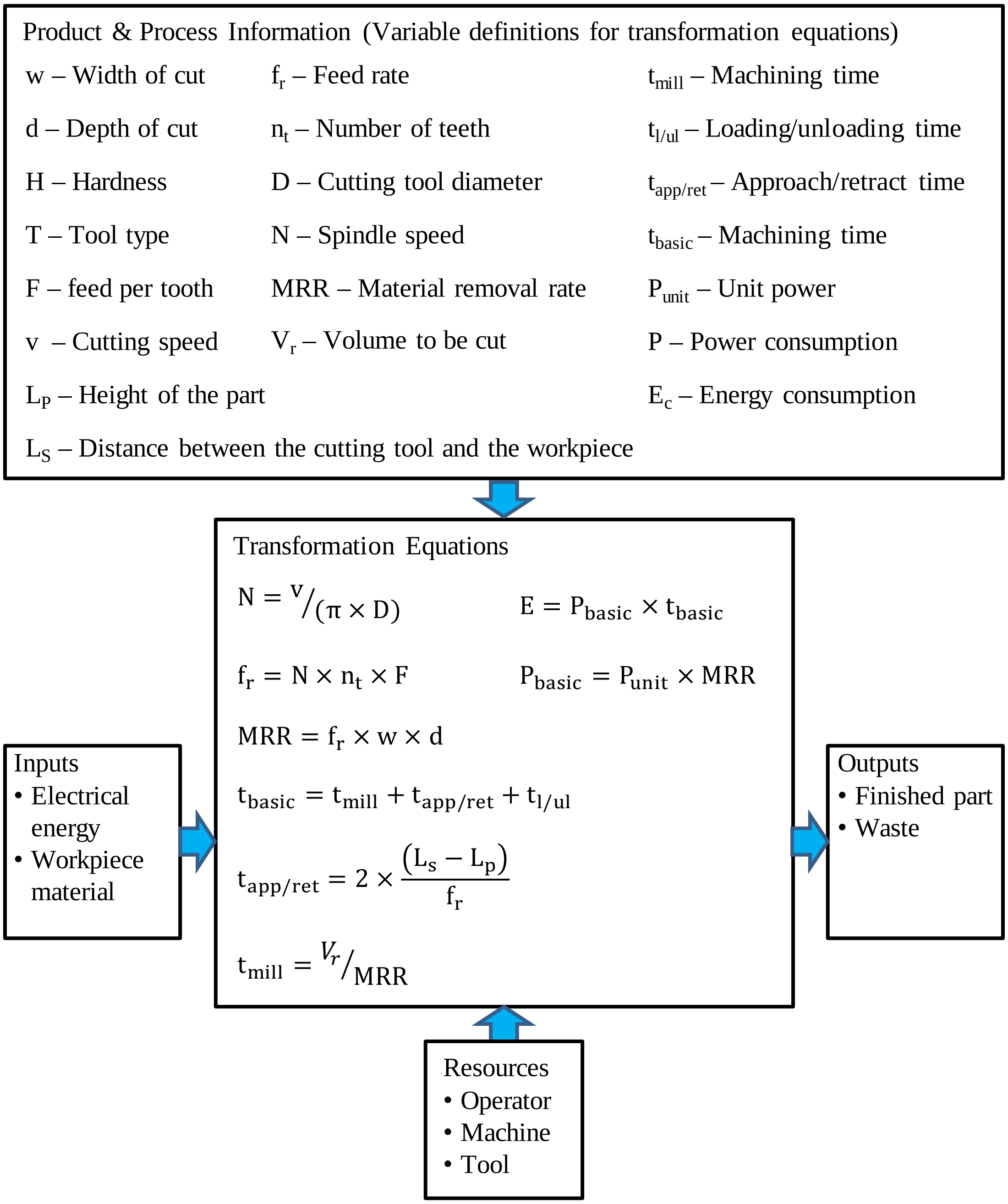
Outputs
- Finished part
- Waste

Resources
- Operator
- Machine
- Tool

Figure 41. Drilling UMP model (based on [67])

Appendix D: Milling UMP Model

Graphical representation of the milling UMP model, including the transformation equations is presented in Figure 42.



Product & Process Information (Variable definitions for transformation equations)

w – Width of cut
d – Depth of cut
H – Hardness
T – Tool type
F – feed per tooth
v – Cutting speed
L_P – Height of the part
L_S – Distance between the cutting tool and the workpiece
f_r – Feed rate
n_t – Number of teeth
D – Cutting tool diameter
N – Spindle speed
MRR – Material removal rate
V_r – Volume to be cut
t_{mill} – Machining time
$t_{l/ul}$ – Loading/unloading time
$t_{app/ret}$ – Approach/retract time
t_{basic} – Machining time
P_{unit} – Unit power
P – Power consumption
E_c – Energy consumption

Transformation Equations

$$N = {}^{v}/_{(\pi \times D)}$$

$$E = P_{basic} \times t_{basic}$$

$$f_r = N \times n_t \times F$$

$$P_{basic} = P_{unit} \times MRR$$

$$MRR = f_r \times w \times d$$

$$t_{basic} = t_{mill} + t_{app/ret} + t_{l/ul}$$

$$t_{app/ret} = 2 \times \frac{(L_s - L_p)}{f_r}$$

$$t_{mill} = {}^{V_r}/_{MRR}$$

Inputs
- Electrical energy
- Workpiece material

Outputs
- Finished part
- Waste

Resources
- Operator
- Machine
- Tool

Figure 42. Milling UMP model (based on [61])

Values of unit horsepower and specific energy for different metals, which are used in the transformation equations of the milling process are presented Table 24.

Table 24. Values of unit horsepower and specific energy

Material	Brinell hardness	Specific energy	
		N-m/mm^3 (sharp)	N-m/mm^3 (dull)
Carbon steel	150-200	1.6	2
	201-250	2.2	2.75
	251-300	2.8	3.5
Alloy steels	200-250	2.2	2.75
	251-300	2.8	3.5
	301-350	3.6	4.5
	351-400	4.4	5.5
Cast irons	125-175	1.1	1.375
	176-250	1.6	2
Stainless steel	150-250	2.8	3.5
Aluminum	50-100	0.7	0.875
Aluminum alloys	100-150	0.8	1
Brass	100-150	2.2	2.75
Bronze	100-150	2.2	2.75
Magnesium alloys	50-100	0.4	0.5

Appendix E: Survey

Recruitment Script

Dear Student,

We would like to invite you to take part in the research project entitled: **Evaluation of Manufacturing Process and System (MaPS) Sustainability Analysis Tool**.

Our objective in this project is to evaluate the ease-of-use of the MaPS tool for conducting economic, environmental, and social impact assessments during product design. To analyze the tool's ease-of-use, we will collect data from you, if you agree to be a part of the research.

This study will involve each individual student completing an activity and responding to a set of questions pertaining to the activities they have completed.

Thank you for your attention and participation. Please let me know if you have any questions regarding the study.

Project Investigator:

Karl R. Haapala, Ph.D.
Associate Professor and Tom & Carmen West Faculty Scholar
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University, Corvallis, Oregon, USA 97331
Email: Karl.Haapala@oregonstate.edu
Phone: (541) 737-3122; Fax: (541) 737-2600

Your Code: __________

__ I DO consent to my answers being used in this research.

__ I DO NOT consent to my answers being used in this research.

Part I: Demographics

A. I am a:

__ Freshman (first year)

__ Sophomore (second year)

__ Junior (third year)

__ Senior (fourth year)

__ Master’s student (M.S., M.Eng., etc.)

__ Doctoral student

__ Other (Explain, optional: ______________________)

B. I am majoring in: ______________________________________

C. My gender is: __ Male __ Female __ Prefer not to say

D. My age is: _______

E. How many years of professional work experience do you have? ___________

F. My previous sustainable design experience includes (describe briefly):

Part II: Perceived Ease-of-Use of the Manufacturing Process and System (MaPS) sustainability analysis tool. Check the box that best describes your agreement with each statement (on a scale of 1 to 7):

1. Learning to operate the MaPS tool would be easy for me.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

2. I would find it easy to get the MaPS tool to do what I want it to do.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

3. My interaction with the MaPS tool would be clear and understandable.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

4. I would find the MaPS tool to be flexible to interact with.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

5. It would be easy for me to become skillful at using the MaPS tool.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

6. I would find the MaPS tool easy to use.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

7. Do you have any additional comments to provide about the ease-of-use of the MaPS tool?

Part III: Perceived Usefulness of the Manufacturing Process and System (MaPS) sustainability analysis tool. Think about the sustainable product design activity that you completed as well as future studies that you might conduct to evaluate and improve product sustainability performance. Check the box that best describes your agreement with each statement (on a scale of 1 to 7):

1. Using the MaPS tool in my job would enable me to accomplish tasks more quickly.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

2. Using the MaPS tool would improve my job performance.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

3. Using the MaPS tool in my job would increase my productivity.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

4. Using the MaPS tool would enhance my effectiveness on the job.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

5. Using the MaPS tool would make it easier to do my job.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

6. I would find the MaPS tool useful in my job.

☐	☐	☐	☐	☐	☐	☐
1	2	3	4	5	6	7
Very strongly disagree	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Very strongly agree

7. Do you have any additional comments to provide about the usefulness of the MaPS tool?

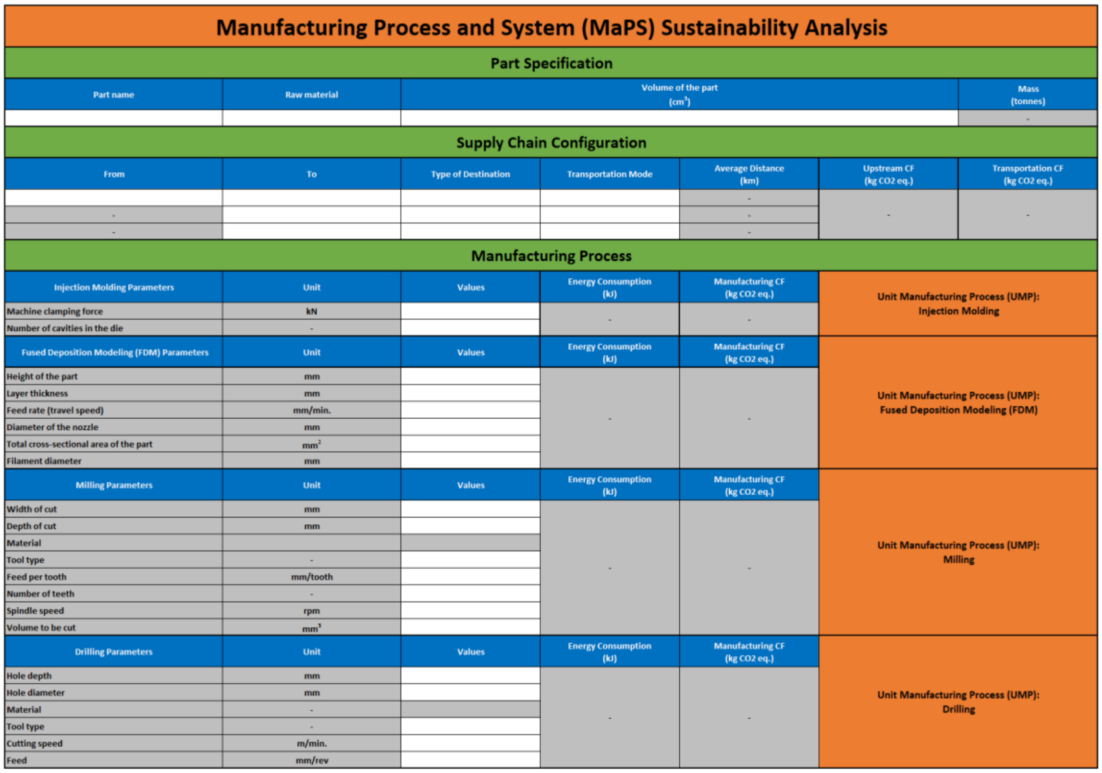
Appendix F: Tutorial of the Manufacturing Process and System (MaPS) Sustainability Analysis Tool

1. Introduction

The Manufacturing Process and System (MaPS) Sustainability Analysis tool is developed as part of a collaborative research project entitled *Constructionism in Learning: Sustainable Life Cycle Engineering (CooL:SLiCE)* [1] supported by the U.S. National Science Foundation. The MaPS tool enables you to assess the effect of different product designs on the environmental (energy use and carbon footprint), economic (cost), and social (number of injuries and illnesses and days away from work) impacts of manufacturing processes and supply chain network configurations.

2. Tasks

Open the Excel file entitled *MaPS Sustainability Analysis Tool*. A message will appear at this step. Select “Don’t update” and then save the file as “Analysis_YourName.” This tool enables you to quantify the sustainability performance of up to five plastic and metal parts within the “Plastic…” and “Metal…” tabs, respectively. Figure 43 presents a screenshot of the tool user interface for plastic parts. Injection molding, fused deposition modeling (FDM), milling, and drilling processes are included in the tool for making plastic parts.



Manufacturing Process and System (MaPS) Sustainability Analysis

Part Specification

Part name	Raw material	Volume of the part (cm^3)	Mass (tonnes)
			-

Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		

Manufacturing Process

Injection Molding Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Machine clamping force	kN		-	-	Unit Manufacturing Process (UMP): Injection Molding
Number of cavities in the die	-				

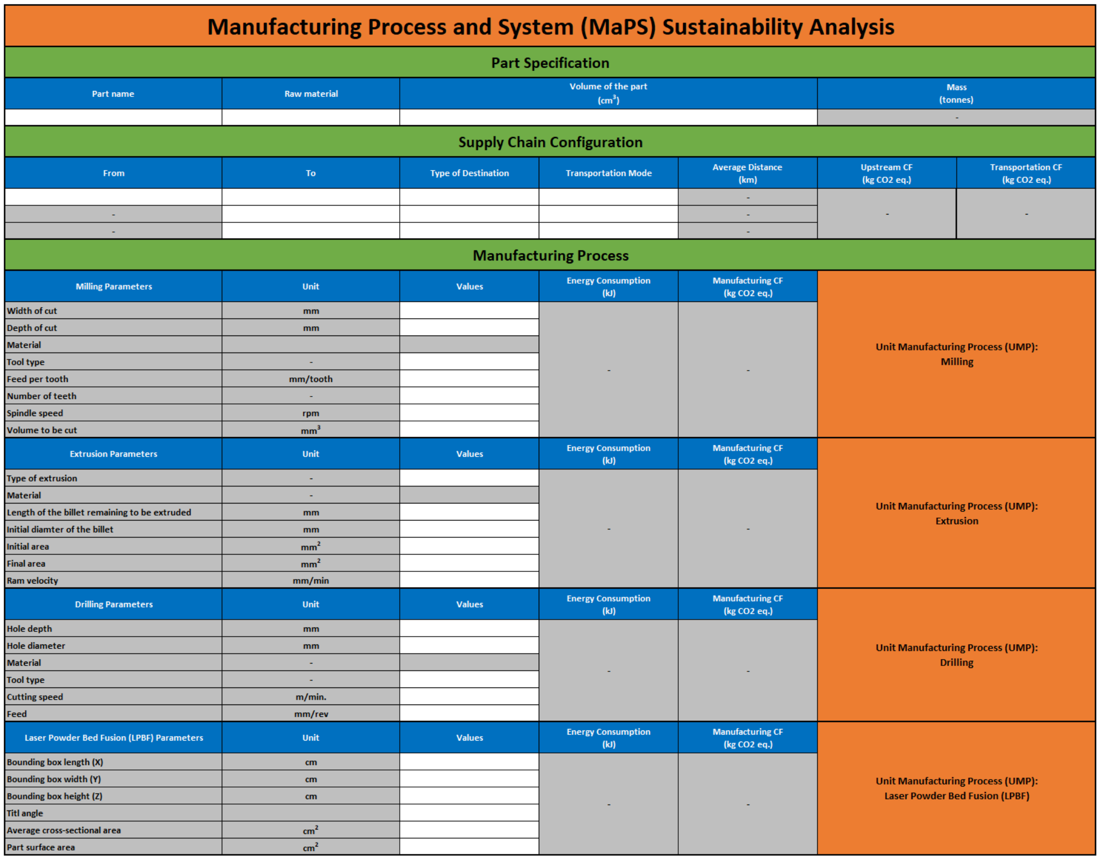
Fused Deposition Modeling (FDM) Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Height of the part	mm		-	-	Unit Manufacturing Process (UMP): Fused Deposition Modeling (FDM)
Layer thickness	mm				
Feed rate (travel speed)	mm/min.				
Diameter of the nozzle	mm				
Total cross-sectional area of the part	mm^2				
Filament diameter	mm				

Milling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Width of cut	mm		-	-	Unit Manufacturing Process (UMP): Milling
Depth of cut	mm				
Material					
Tool type	-				
Feed per tooth	mm/tooth				
Number of teeth	-				
Spindle speed	rpm				
Volume to be cut	mm^3				

Drilling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Hole depth	mm		-	-	Unit Manufacturing Process (UMP): Drilling
Hole diameter	mm				
Material	-				
Tool type	-				
Cutting speed	m/min.				
Feed	mm/rev				

Figure 43. MaPS Sustainability Analysis Tool user interface for plastic parts

A screenshot of the tool user interface for metal parts is presented in Figure 44. Laser powder bed fusion (LPBF), milling, drilling, and extrusion are the manufacturing processes in the tool for making metal parts.



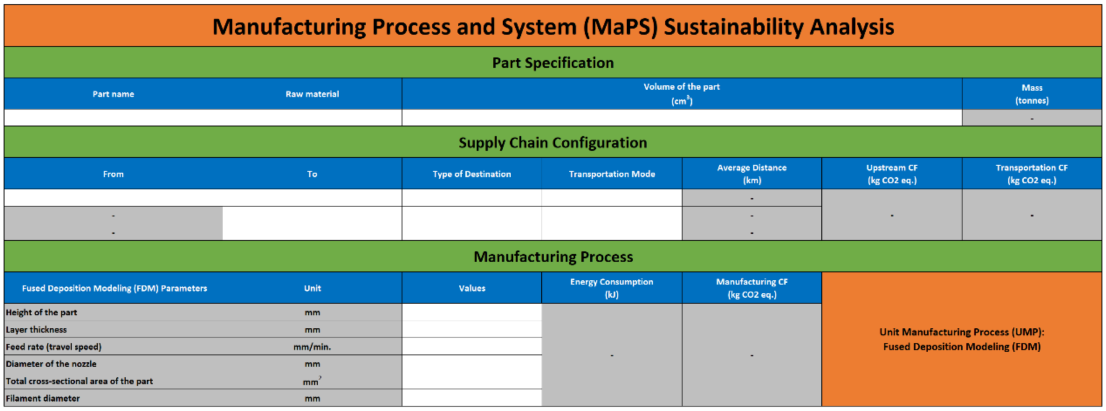
Manufacturing Process and System (MaPS) Sustainability Analysis						
Part Specification						
Part name	Raw material	Volume of the part (cm^3)			Mass (tonnes)	
					-	
Supply Chain Configuration						
From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		
Manufacturing Process						
Milling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	Unit Manufacturing Process (UMP): Milling	
Width of cut	mm		-	-		
Depth of cut	mm					
Material						
Tool type	-					
Feed per tooth	mm/tooth					
Number of teeth	-					
Spindle speed	rpm					
Volume to be cut	mm^3					
Extrusion Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	Unit Manufacturing Process (UMP): Extrusion	
Type of extrusion	-		-	-		
Material	-					
Length of the billet remaining to be extruded	mm					
Initial diamter of the billet	mm					
Initial area	mm^2					
Final area	mm^2					
Ram velocity	mm/min					
Drilling Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	Unit Manufacturing Process (UMP): Drilling	
Hole depth	mm		-	-		
Hole diameter	mm					
Material	-					
Tool type	-					
Cutting speed	m/min.					
Feed	mm/rev					
Laser Powder Bed Fusion (LPBF) Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	Unit Manufacturing Process (UMP): Laser Powder Bed Fusion (LPBF)	
Bounding box length (X)	cm		-	-		
Bounding box width (Y)	cm					
Bounding box height (Z)	cm					
Titl angle						
Average cross-sectional area	cm^2					
Part surface area	cm^2					

Figure 44. MaPS Sustainability Analysis Tool user interface for metal parts

The interfaces for both plastic and metal parts have three main sections:

- Part Specification
- Supply Chain Configuration
- Manufacturing Process

Input information ONLY into the white cells. To describe each of the sections mentioned above, a case study is presented below for making a plastic part using fused deposition modeling (FDM) process.



Manufacturing Process and System (MaPS) Sustainability Analysis

Part Specification

Part name	Raw material	Volume of the part (cm^3)	Mass (tonnes)
			-

Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
				-	-	-
-				-		
-				-		

Manufacturing Process

Fused Deposition Modeling (FDM) Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	Unit Manufacturing Process (UMP): Fused Deposition Modeling (FDM)
Height of the part	mm		-	-	
Layer thickness	mm				
Feed rate (travel speed)	mm/min.				
Diameter of the nozzle	mm				
Total cross-sectional area of the part	mm^2				
Filament diameter	mm				

Figure 45. The three main sections of the MaPS Sustainability Analysis Tool (model interface of fused deposition modeling process)

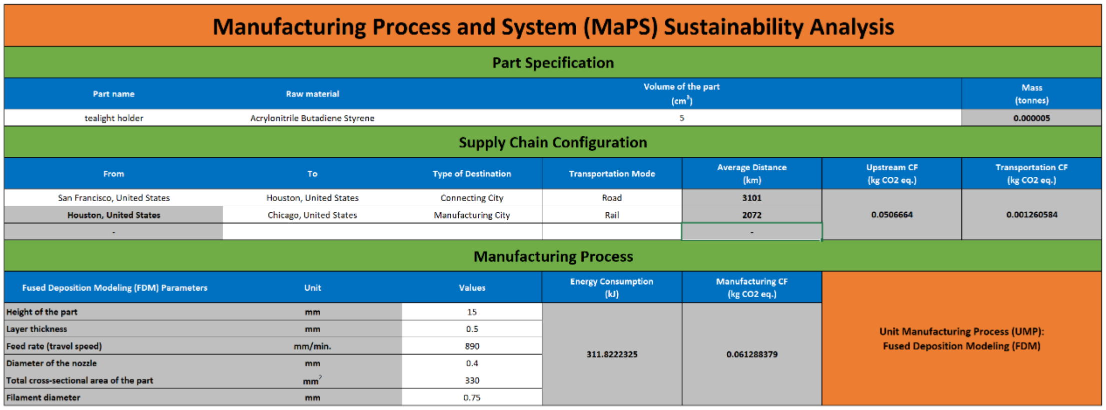
The first section (Part Specification) allows you to enter information about the part design. First, enter the name of the part (e.g., tealight holder) in the *Part Name* cell. Two types of plastic, acrylonitrile butadiene styrene (ABS) and cellulose acetate butyrate (CAB), are provided as raw materials in the database. Choose ABS as the type of material in the *Raw Material* cell. Next, provide the part volume under the *Volume of the Part* cell in cubic centimeters. Input 5cm^3 for the part volume. This value is taken from Manoharan et al. [2] for a tealight holder. The part mass will be calculated automatically based on your inputs and information in the database.

The second section (Supply Chain Configuration) displays a From-To Chart for your desired supply chain network design. To deliver raw material to the manufacturer (assumed to be located in the United States), different suppliers across the world as well as different transportation modes and connecting cities are provided in the database. Connecting cities are transfer points in the supply chain network, and no manufacturing occurs at these locations.

First, in the white cell of the *From* column, select San Francisco, California using the drop-down menu as the *supplier location* and in the *To* column select Houston, Texas as the *connecting city*. Select *road* as the transportation mode. You will see that Houston, Texas is added automatically to the next row in the grey cell under the *From* column.

Now, you will need to determine the next destination in this supply chain network. Similar to the previous step, select Chicago, Illinois from the drop-down menu under the *To* column and define it as the *manufacturing city*. Select the transportation mode to send the materials from Houston to Chicago as *rail*. You can modify these selections later to see the impact of choosing different manufacturing and connecting cities, as well as transportation modes.

Finally, you will define the manufacturing process for making the selected part. FDM is the manufacturing process used here for making plastic parts. As shown in Figure 45 (Manufacturing Process section), six parameters are required for modeling the FDM process in the Manufacturing Process and System (MaPS) Sustainability Analysis tool. Input 15mm, 0.5mm, 890mm/min., 0.4mm, 330mm^2, and 0.75mm for the height of the part, layer thickness, feed rate (travel speed), diameter of the nozzle, total cross-sectional area of the part, and the filament diameter, respectively. These parameters and values are taken from Manoharan et al. [2]. The completed FDM model interface is presented in Figure 46.



Manufacturing Process and System (MaPS) Sustainability Analysis

Part Specification

Part name	Raw material	Volume of the part (cm^3)	Mass (tonnes)
tealight holder	Acrylonitrile Butadiene Styrene	5	0.000005

Supply Chain Configuration

From	To	Type of Destination	Transportation Mode	Average Distance (km)	Upstream CF (kg CO2 eq.)	Transportation CF (kg CO2 eq.)
San Francisco, United States	Houston, United States	Connecting City	Road	3101	0.0506664	0.001260584
Houston, United States	Chicago, United States	Manufacturing City	Rail	2072		
-				-		

Manufacturing Process

Fused Deposition Modeling (FDM) Parameters	Unit	Values	Energy Consumption (kJ)	Manufacturing CF (kg CO2 eq.)	
Height of the part	mm	15	311.8222325	0.061288379	Unit Manufacturing Process (UMP): Fused Deposition Modeling (FDM)
Layer thickness	mm	0.5			
Feed rate (travel speed)	mm/min.	890			
Diameter of the nozzle	mm	0.4			
Total cross-sectional area of the part	mm^2	330			
Filament diameter	mm	0.75			

Figure 46. The FDM model interface with values entered for the case study

The estimated energy and carbon footprint, cost, number of injuries and illnesses, and days away from work are reported in the tabular format in a tab entitled "Summary_Results" for upstream, transportation, and manufacturing processes. This tab includes the information of all the five parts for different plastic and metal manufacturing processes. In addition, the graphical representations (pie charts) of the sustainability assessment results are provided for each part. To view them, go to the tabs starting with "Charts" (e.g., Charts_Part 1). Each of these tabs includes the sustainability assessment results of both plastic and metal manufacturing processes. Thus, you may need to scroll to find the manufacturing process(es) used for making the intended part. For this case study, scroll to find the pie charts of the FDM process.

Save your file for later reference.

3. References

[1] Raoufi, K.†, K. Park, M.T.H. Khan, K.R. Haapala, C.E. Psenka, K.L. Jackson, G.E.O. Kremer, K.–Y. Kim, 2019, “A Cyberlearning Platform for Enhancing Undergraduate Engineering Education in Sustainable Product Design,” Journal of Cleaner Production, Vol. 211, pp. 730-741, doi: 10.1016/j.jclepro.2018.11.085.

[2] Manoharan, S., D. Harper, K.R. Haapala, 2018, “Aggregating Unit Process Models to Enable Environmental Impact Characterization of Polymer-Based Hybrid Manufacturing,” Proceedings of the 16th Global Conference on Sustainable Manufacturing (GCSM), Lexington, KY.

Appendix G: Activity Description

IMPROVING PRODUCT SUSTAINABILITY PERFORMANCE
MANUFACTURING PROCESS AND SYSTEM (MAPS)
SUSTAINABILITY ANALYSIS TOOL

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1. From the folder entitled *Hexacopter*, open the *Hexacopter.SLDASM* CAD file (save the assembly file and part files in the same folder for compatibility with SolidWorks).

2. Open the *MaPS Sustainability Analysis Tool* (Excel) to analyze your product. Before completing your own analysis, follow the instructions for the example case study in the tutorial entitled "MaPS_Tutorial.docx."

NOTE: To analyze the part using the MaPS tool, you need the information as described in the tutorial and product geometry data from the CAD files.

3. Explore potential changes you could make to the hexacopter part designs, manufacturing processes, and supply chains to improve sustainability performance. Observe the impacts these changes have on the provided sustainability metrics (i.e., energy use, carbon footprint, cost, number of injuries and illnesses, and days away from work). For example, you might compare the differences of machining vs. additive manufacturing or the effects of using plastic- vs. metal-based additive manufacturing processes.

4. When you finish, please complete the survey developed to investigate the ease-of-use and usefulness of the MaPS Sustainability Analysis Tool. You can find the survey using the following link: <*link*>