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Analyzing environmental sustainability methods for use earlier in the product lifecycle

Michael P. Brundage[a,1,*], William Z. Bernstein[a,1], Steven Hoffenson[b], Qing Chang[c], Hidetaka Nishi[c], Timothy Kliks[b], KC Morris[a]

[a] *National Institute of Standards and Technology, Gaithersburg, MD, 20899, USA*
[b] *Stevens Institute of Technology, Babbio Center, Hoboken, NJ 07030, USA*
[c] *Stony Brook University, Stony Brook, NY 11794, USA*

Abstract

Environmental sustainability information in the manufacturing industry is not easily shared between stages in the product lifecycle. In particular, reliable manufacturing-related information for assessing the sustainability of a product is often unavailable at the design stage. Instead, designers rely on aggregated, often outdated information or make decisions by analogy (e.g., a similar manufacturing process for a similar product yielded X and Y results). However, smart manufacturing and the Internet of Things have potential to bridge the gap between design and manufacturing through data and knowledge sharing. This paper analyzes environmental sustainability assessment methods to enable more accurate decisions earlier in design. The techniques and methods are categorized based on the stage they apply to in the product lifecycle, as described by the Systems Integration of Manufacturing Applications (SIMA) reference architecture. Furthermore, opportunities for aligning standard data representation to promote sustainability assessment during design are identified.

Keywords: Sustainable Design, Sustainable Manufacturing, Environmental Assessment, Analysis Tools, Lifecycle Assessment, Smart Manufacturing

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1. INTRODUCTION

Manufacturing has a large impact on the environment, including high energy consumption, waste generation, and greenhouse gas emissions. Energy consumption in the manufacturing industry rose approximately 3.7 % from 2010 to 2014 from 5.38 billion kWh to 5.58 billion BTU [1]. This marked the first time since 2002 that energy consumption had risen in a four year period in the industrial sector. On top of this, American industrial facilities

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[*] Address all correspondence to this author.
[1] Equal contribution by both authors.

generate 7.6 billion tons of waste annually [2] and accounted for emissions of 6.587 billion metric tons of carbon dioxide (CO_2) equivalent [3] in 2015. This represented 21 % of all 2015 greenhouse emissions in the US, with transportation contributing 27 % and electricity production contributing 29 %. Considering the downstream manufacturing supply chain, which is larger than the manufacturing industry in itself and includes transportation and electricity generation among other considerations [4], manufacturing accounts for more than half of the total environmental impact of the US economy [5].

To reduce the impact that manufacturing has on the environment, a variety of methods are deployed at multiple stages of the product lifecycle. For example, to reduce energy usage during production, the Environmental Protection Agency (EPA) created the energy star program for industrial energy management in 1992 [6]. Through this program, General Motors (GM) reduced energy consumption by 40 % and CO_2 emissions by 41 % over 20 years while simultaneously increasing productivity [7]. This is a savings of over $435 million for their manufacturing plants, which make up 75 % of all energy consumed at GM. One area where GM was able to save energy was through the "Shut It Off" campaign where non-essential, energy intensive equipment was switched off while not in use [8], but this effort was only focused on the production stage of the product lifecycle.

Less explored opportunities for environmental impact reduction still remain when manufacturing knowledge is readily available to designers during product design. For example, if a manufacturing process for a part feature is energy intensive, a product designer might consider an alternative feature that requires a less energy intensive process and still meets specifications. Lifecycle Assessment (LCA) practitioners often ignore impacts from manufacturing in certain scenarios since the resultant magnitudes of impact are often less than cut-off values of the analysis, making manufacturing impacts seem insignificant compared to the rest of the lifecycle; however, this practice can be short sighted. In response, Suh [9] presented scenarios illustrating cut-off thresholds that could potentially skew hotspot identification and alternative comparison. Furthermore, Löfgren et al. [10] argued that the current LCA framework, from ISO 14000 [11], does not account for particular perspectives, such as a production line manager, supply chain procurement engineer, or a design engineer, which could result in varying opinions or inaction. One case study within SKF (Svenska Kullagerfabriken AB), a Swedish ball bearing original equipment manufacturer (OEM), provided different results for lifecycle impacts when considering only certain portions of the lifecycle [12]. On a similar note, Reap et al. [13] also discussed significant shortcomings in the current practice of LCA due to allocation and cutoff challenges. Such examples illustrate hurdles for individual stakeholders in the lifecycle, such as manufacturers, to introduce effective change in the systems they control. To help address these hurdles, this paper focuses on understanding existing tools and techniques for assessing and improving environmental sustainability of manufacturing activities, specifically. This paper does not address the social and economic tenants of sustainability; therefore, when sustainability is mentioned, it is only accounting for environmental sustainability.

Throughout the product lifecycle, the ability to reduce the environmental impact of each stage lessens as the product progresses through the lifecycle. The lifecycle begins during conceptual design. The conceptual design stage's influence on production has been studied extensively. It is estimated that 70 to 80 percent of the total cost of a product is committed during the design stage [14]. Correspondingly, it is postulated that a majority of the sustainability characteristics of a product are attributed during the early design stage as well [15]. Once the detailed design stage is completed, part geometry, product specifications including material, and initial process plans are all fixed. Such product characteristics greatly influence all following product lifecycle stages from an environmental perspective. For example, material choice will influence scrap rate during manufacturing, usage consumption patterns (e.g., aluminum vs. steel truck-beds), and end-of-life (EOL) options (e.g., recyclability vs. remanufacture-ability). All in all, the design stage casts an "environmental shadow" across the downstream processes of the lifecycle.

Currently, the lack of feedback from manufacturing to product designers limits the designers ability to reduce environmental impacts from the manufacturing phase. Once a product is designed, manufacturers have little opportunity to improve its sustainability. The significant impact of product design on sustainability underscores the need for the projection of downstream activities back to design to spur more prudent decision making. Hedberg Jr et al. [16] found that facilitating availability of manufacturing knowledge early in design can lead to reduced production cycle time and other significant advantages. The authors extrapolate this applies to sustainability effects as well. However, many barriers exist to realizing sustainable manufacturing. Bhanot et al. [17] describe the following barriers: (1) lack of awareness of sustainability concepts, (2) lack of standardized metrics and performance benchmarks and (3) high cost of initially implementing sustainable technology. This paper addresses the first issue by categorizing sustainability techniques based on the stage of the product lifecycle at which they are most useful. This categorization helps identify specific research gaps in analysis techniques and suggests best practices for developing or modifying tools and defining standards for sustainable design practices.

Existing techniques specific to each stage of the product lifecycle, such as methods specific to a product designer or a manufacturing engineer, are fragmented into silos with little knowledge exchanged between them. For example, product designers may focus on material selection to reduce environmental impacts, while manufacturing engineers may focus on energy reduction. Without an understanding of the impact of the material on the manufacturing process, the two goals may be at odds with one another. To make the situation more challenging, designers may not be aware of how their choices influence the manufacturing processes.

Methods for sharing this type of information between the different engineering disciplines and lifecycle stages have yet to be developed and pose wide-ranging challenges including the lack of a shared vocabulary, the struggle of mismatched conceptual orientations, and competing business objectives. Ultimately, a basis is needed for defining guidelines that will help designers incorporate fundamental principles for improving manufacturing efficiency and reducing environmental impacts into their designs. These guidelines will require two common underpinnings: 1) common vocabulary and 2) methods for representing design requirements. Existing standards related to product design and sustainability analysis may provide a starting point for this work.

Sustainability analysis standards for manufactured products have evolved in silos. The prevailing approach to accounting for a product's environmental impact is the ISO 14000 series of standards for Lifecycle Assessment (LCA). The ISO 14000 series provides guidelines for conducting an environmental analysis through LCA on products, processes and systems [18]. The LCA method can be applied to estimate the impact of a final product by accounting for the impacts across all its full lifecycle from resource extraction to end of life. Conducting a full analysis assumes a detailed understanding of how and where the product was produced and how it will be disposed of. It can be costly to complete, taking significant investments in both time and data. To reduce the burden of full comparative LCAs, software vendors and government agencies developed databases, such as the European reference Lifecycle Database [19] and the United States Lifecycle Inventory Database [20], of reusable "unit processes" that can be linked together to estimate the environmental impact of a product. Even so, full LCAs are not commonly used in design. Within the LCA Community, ecoSpold is the de facto standard data representation for unit processes in environmental analyses [19] and could provide a starting point for integrating lifecycle data into design once a conceptual basis for this integration is established.

Two standards efforts are emerging which focus on the manufacturing process itself. ASTM standards for sustainable manufacturing provide guidelines for reducing the environmental impact of manufacturing processes by setting environmental objectives and applying continuous improvement methods to address those objectives. See ASTM E2986-15 [20], ASTM E3012-16 [21], and ASTM E3096-17 [22]. Efforts based on these standards are ongoing to develop a repository of models of manufacturing processes, called Unit Manufacturing Process (UMP) models, that highlight factors that influence their environmental impacts [23]. ISO 20140 establishes principles for classifying manufacturing data and characterizing its effect on the overall environmental influence of manufacturing systems [24]. While this data will be necessary for informing design choices, no standard methods are currently available for reflecting these improvements into either LCA or design decision making.

More nuanced efforts are underway to understand the interplay of a product's design in terms of its geometric and material characteristics with the manufacturing techniques that will be used in production. This knowledge will provide designers with much more control over the environmental impacts. In LCA, sustainability evaluations are often based on the surface area of material produced or treated (e.g., sheet rolling or laminating) or the mass of material shaped (e.g., casting or machining). For design attributes, such as geometric characteristics of individual features, estimating environmental impact based only on mass is far from precise. While currently no standards specific to sustainability exist in this area, standards such as the Standard for the Exchange of Product Model Data (STEP) [25] which supports the definition of product geometry and material choice may be a starting point for a common vocabulary leading to design rules.

While all of these approaches share the common goal of reducing the environmental impacts of manufacturing products, the fundamental principles on which they are based and their operational concepts vary widely. Even the vocabularies they use are not fully compatible. Existing standards form a basis for integrating these world views but work is still needed to identify their semantic interoperability potential. In addition, as will be seen below, research in other manufacturing lifecycle stages are showing similar opportunities for reducing environmental impact but these areas still lack standards on which to base these integration capabilities.

This paper analyzes widely-used sustainability assessment methods and techniques applied during the different stages in the product lifecycle to discover opportunities to share information across the product manufacturing lifecycle. While many research articles discuss sustainability methods and techniques for each stage of the lifecycle [26–30], few attempt to analyze these methods and techniques across all stages. The authors begin by searching for research works related to each activity (or subactivity) of the Systems Integration of Manufacturing Applications (SIMA) reference architecture [31]. Since there are many research works for each activity, the authors limit the selection to a subset of methods or tools that can be linked with methods or tools from other activities. This paper provides a vision of how tools and methods can be linked across the full product lifecycle. The authors note when a tool is not explicitly used for sustainability assessment, but can be adapted for sustainability purposes. Literature review papers that cover a variety of tools or methods related to an activity are presented in the beginning of their subsequent section.

One goal of this paper is to categorize these techniques and methods according to their role in the product lifecycle. When methods span more than one stage of the lifecycle, the authors discuss them at length for one stage and briefly discuss other stages where they might also apply. The stages addressed in this work are adapted from the SIMA reference architecture include product design (Design Product), process planning (Engineer Manufacture of Product), manufacturing system design (Engineer Production System), and manufacture of the product (Produce Products), as shown in the top of Fig. 1.

The objective is to identify opportunities to use downstream information to enable designers to more accurately estimate, predict, and anticipate environmental performance of a product and its production processes. Figure 1 illustrates the complexity and interconnectedness of a product's information flow. Flow of information is signified by blue arrows, while material flow is represented by red arrows. Dotted arrows show secondary or auxiliary flow of both material and information. To properly discuss sustainability of products, decision makers must be able to understand the implications of each box in this diagram. The traditional LCA technique assumes the traditional lifecycle perspective, from material extraction to disposal, presented by the thick red line in Fig. 1. However, when considering all information used in each stage, this perspective might overlook some important factors, such as environmental impact of manufacturing as discussed above, that could improve design choices. Bernstein et. al [32] demonstrated that designers have issues in making simple redesign decisions, even after a rigorous LCA. This makes it almost impossible for non-experts to approach sustainability decisions with an appropriate frame of reference. For example, significant uncertainties result from poor data quality, incorrect, non-transparent, or poorly documented assumptions, and a lack of site-specific lifecycle inventories [33]. Rigorous documentation and information models representing changes to sustainability assessment are still required [34].

The rest of the paper is structured as follows. Section 2 first briefly outlines the SIMA reference architecture, then it presents sustainability analysis methods and techniques during

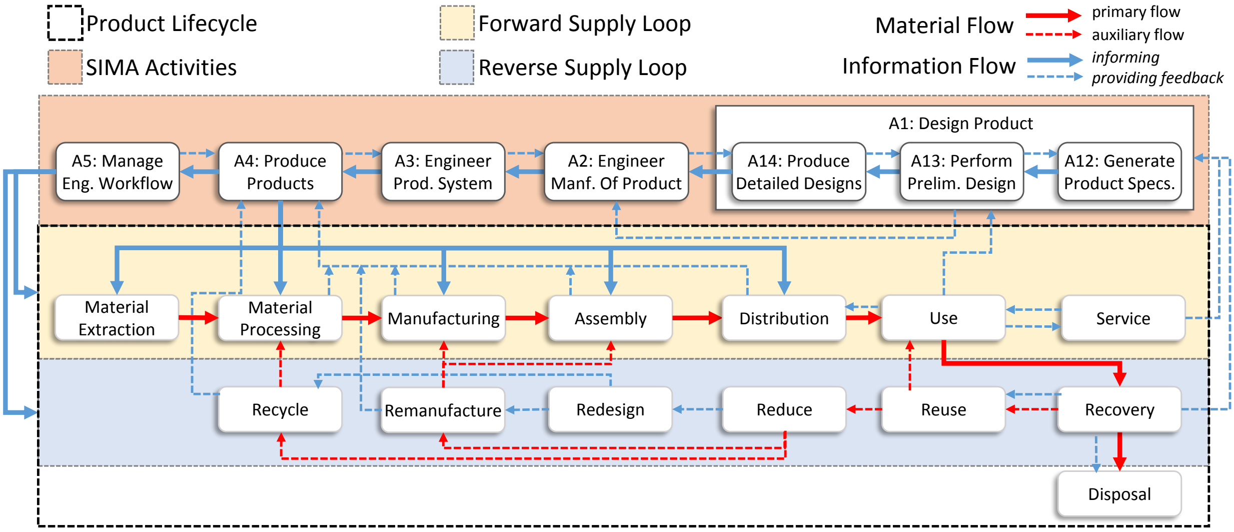

Figure 1: Relationships between SIMA activities and the traditional product lifecycle. Red and blue arrows indicate material and information flow, respectively. The dotted blue arrows indicate feedback to other activities/stages that could improve environmental decisions.

(1) the product design stage, (2) the process planning phase, (3) the design process of the manufacturing system, and finally (4) the actual manufacture of the product. Section 3 summarizes the key takeaways and observed challenges based on our analysis. Lastly, in Section 4, we provide a detailed discussion on improving sustainability assessment tools and in Section 5 we present conclusions, research gaps, and future research opportunities.

2. STUDYING PHASES OF THE SIMA REFERENCE ARCHITECTURE

The SIMA reference architecture is an activity model developed at the National Institute of Standards and Technology (NIST) to describe principal activities involved in design of a product through manufacture [31]. It addresses product design engineering, manufacturing engineering, production systems engineering, and production activities, corresponding to the four top level activities: (1) Design Product, (2) Engineer Manufacture of Product, (3) Engineer Production System, and (4) Develop Products. Shown in Figs. 1 and 2, the main activities of the SIMA architecture are consistent with recent developments in the Internet of Things reference models, such as the German Reference Architecture Model Industrie 4.0 (RAMI 4.0) or work from the Industrial Internet Consortium (IIC), where SIMA activities are congruent with the lifecycle aspect of the RAMI 4.0 model [35]. The SIMA reference architecture was selected to categorize sustainability analysis techniques because of the higher level of detail for each lifecycle activity as compared to the RAMI 4.0 architecture or IIC work.

Each of the four top level activities are organized into multiple sub-activities, as seen in Fig. 2. These sub-activities range from product design through manufacture and identify

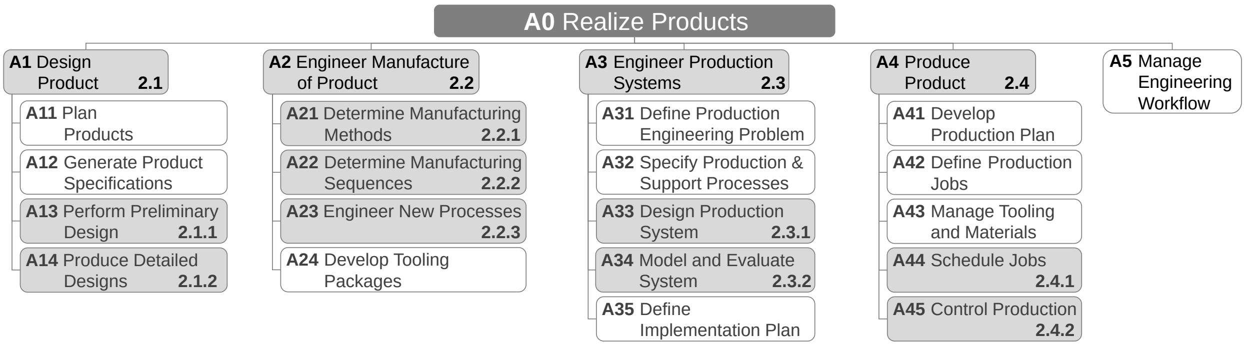

Figure 2: SIMA architecture hierarchy. Boxes highlighted in grey denote stages that were studied throughout this paper with their corresponding section numbers.

the information flows required to perform a technical activity efficiently and effectively. The original purpose of the architecture was to identify functions and interfaces required for manufacturing application software systems. In this paper, the architecture is used to create a framework for more robust environmental sustainability analysis during product design. The SIMA architecture exhibits a forward-feeding flow of information with little downstream knowledge returning to the product design stage. The authors' intention is to define appropriate feedback flows. This paper categorizes sustainability methods into the four main SIMA activities and their subactivities to analyze gaps and opportunities to use knowledge earlier in product design. Future work will investigate expanding the SIMA architecture for environmental sustainability assessment, extending the work in GreenSIMA [36]. Figure 2 provides a roadmap for Section 2. The section and subsection headings are organized based on a subset of the SIMA architecture activities. This analysis only covers the boxes highlighted in light grey.

2.1. DESIGN PRODUCT METHODS

The SIMA reference architecture defines the Design Product activity as "identify and conceptualize a marketable product, and create the complete description of it" [31]. This activity has two main subactivities: Perform Preliminary Design and Produce Detailed Design.

2.1.1. Perform Preliminary Design

This subactivity decomposes the design problem into a set of component design problems and defines specifications for each component. Traditionally, design is broken into three primary stages: conceptual design, embodiment design, and detailed design. The SIMA reference architecture deals with design in two primary activity stages: (1) perform preliminary design and (2) produce detailed design. For simplicity, the authors consider only the conceptual design stage for Perform Preliminary Design.

Incorporating sustainability-related requirements into design is often referred to as "ecodesign," and a number of methods and tools have been developed with this objective. Ramani et al. [15] suggested that most ecodesign tools fall within three high-level categories, based on (1) LCA, (2) checklists, and (3) quality functional deployment (QFD). Checklist-based tools prompt stakeholders with qualitative assessments of product attributes. Often, assessment results are riddled with subjectivity and uncertainty influenced by the stakeholders perspective or ignorance. Used throughout the automobile industry, QFD is a semi-quantitative technique for relating customer requirements to product features or functions. QFD-based ecodesign tools incorporate eco-conscious considerations into the design process yet still suffer from subjectivity due to limits on the user's knowledge of sustainability-related topics. Since QFD requires users to judge the importance of product features and customer requirements, inputs directly rely on expert knowledge and intuition. To avoid bias, one promising approach is to incorporate eco-indicator estimation models into the design process [37]. Here, primary challenges are related to data, including its availability, uncertainty, and relevancy.

Ramani et al. [15] found that, in general, the more quantitative the tool, the less relevant it is for conceptual design. Often, during the conceptual design stage, teams lack the necessary knowledge to estimate lifecycle impact, including material specifications, user behavior, and end-of-life scenarios. As a result, relating sustainability information to conceptual design has remained an expert-driven practice with little support besides general and basic rules, principles, and best practices, such as incorporating modular design features to extend the product through multiple lifecycles. That said, some attempts at quantification have been made. One method, initially proposed by Brezet and van Hemel, is the MET-Matrix (Materials, Energy, Toxic emissions) [38]. This method uses two matrices, one that helps practitioners list environmental concerns related to materials, energy, and toxicity while the other qualitatively rates the severity of the identified issues. In practice, this method is used in conceptual design [30]. Another similar method is the Environmentally Responsible Product/Process Assessment Matrix (ERP) [39], wherein the matrix's rows represent lifecycle stages and the columns relate to environmental concerns. Within each cell, the practitioner is asked to rate the studied system on a scale, 0 to 4, based on its perceived performance. Similar management tools have been proposed for assessing the priority of specific environmentally related concerns [40, 41]. However, all of these methods include ratings based on expert (or practitioner) knowledge, introducing significant bias. Also, the authors have no evidence that these tools have received wide adoption in practice.

To better inform decisions and decrease ambiguity at design, Design for Manufacture (DfM) approaches bring manufacturing-related factors into the product design process. DfM includes a broad array of processes and tools that help designers and process engineers develop easily manufacturable products with faster design cycles, higher production volumes, and quicker production times [42]. Taking manufacturing issues into account as early as possible during design can help minimize production costs and environmental impacts, and many DfM methods are intended for the preliminary design stages [43]. These methods include organizational strategies and adopting systemic design principles, such as reducing the number of components, employing modular architectures, and using standard components [44].

Traditional DfM seeks to simplify product structure and choose the lowest-cost materials and processes early in the design process [45]. Cost estimates are made based on measures such as the total number of parts, ease of handling of the system, and the type and number of fastening mechanisms. Each part is analyzed, assembly time is calculated based on estimated processes, and potential problems are addressed through re-design [46]. Catalogs of standardized parts are often used to select those with the lowest cost or highest ease of manufacturability and assembly. Fabricius [47] identified a set of DfM rules and parameters to help narrow down the design of a system, using objectives, evaluations, design parameters, identification of primary functions, and verification tests. This approach can lead to conceptual designs that are easier to assemble and use economically viable processes and materials [48]. Seeing that manufacturing costs are often directly correlated with environmental impacts (e.g., reducing energy consumption benefits both environmental and economic costs), there is an opportunity to leverage existing sustainability standards and best practices with traditional DfM methods for use in the conceptual design phase.

2.1.2. Produce Detailed Design

Detailed design produces all necessary specifications for each subsystem of a product. This includes drawings, geometries, materials, and assembly drawings. Since this stage houses more information about a product, more quantitative, rigorous environmental estimation and assessment is possible.

Since the release of the ISO14000 series, the use of software to perform detailed environmental analyses of products and processes has steadily increased. The two most licensed software that are specifically targeted at conducting detailed Lifecycle Assessments are SimaPro [49] and GaBi [50]. These systems are difficult to operate without an appropriate level of knowledge of LCA-related concepts, e.g., unit processes, allocation and assessment weighting schemes. Alternatively, some software has been augmented with add-on packages for eco-design, e.g., Cambridge Engineering Selector (CES) Edupack Eco Audit Tool [51, 52] and SolidWorks Sustainability Xpress Tool [53]. These packages rely on estimations and do not provide intuitive visualizations for reporting results. Furthermore, these packages do not enable “what-if” scenario analyses, in which the user can compare “as-is” and “to-be” designs side by side. To the best of the authors’ knowledge, the only commercially available, licensed software that supports side-by-side comparisons of two design options is Sustainable Minds, primarily focusing on environmental impacts of associated material and manufacturing processes [54].

Though a number of eco-design tools are proposed in literature, exactly determining their range of adoption in practice is difficult. Many of these tools simplify or coordinate LCA preparation and accounting. The MECO (Materials, Energy, Chemicals, and Others) method [55] simplifies listing the relevant inputs and outputs within a given lifecycle inventory. Research suggests that the MECO method is most effective when used as a screening procedure during design before transitioning into a more rigorous LCA. Other methods similar to the MECO generally fall within the category of streamlined LCA procedures [56]. The main limitation of streamlined LCAs is that users are not required to construct data-driven models to assess the environmental impacts. Instead, they qualitatively score expected attributes of the product’s lifecycle based on experience and similar products, increasing the possibility of errors introduced through user bias.

Several software tools have been developed to support material and process selection. One such tool, WiseProM [57], uses three databases, available processes, materials, and compatibility between the two. Taking into account the industry, material requirements, and form requirements, WiseProM suggests suitable, low-cost materials and process sequences. The Manufacturing Advisory Service (MAS) [58] is a web-based tool that provides a ranked list of material and process options as information about production quantity, tolerances, product size and overall shape, and cost requirements. Another popular tool is the CES, which showcases interactive graphical analyses of various properties, and includes options for eco-design using lightweight, hybrid materials [51, 52].

Traditional methods and tools are used in DfM during late-stage design. Failure Modes and Effects Analysis (FMEA) [59] evaluates each possible failure mode of a system and the mode's impact on performance, safety, and maintenance. The results rank failure modes by probability and severity, which can help a team adjust materials, processes, or overall design to reduce these potential risks. Modular function deployment (MFD) [60] guides design engineers to integrate multiple functions of a product into a singular module, aiming to simplify manufacturing processes by removing unnecessary components. This approach begins with a QFD to establish customer needs and functional requirements, then applies a module indication matrix (MIM) for combining components. The variety reduction program (VRP) [61] focuses on decreasing complexity costs by reducing the number of parts and processes through a parts index, a production process index, and a control point index. The VRP classifies costs into variety costs, driven by the variety of parts and processes; function costs, referring to product specifications, design functions, and product construction methods; and control costs, caused by the facility, design team, and materials department.

2.1.3. Key Takeaways

As described above, design is a critical stage in the lifecycle for decision making. The so-called “environmental shadow” of design decisions casts itself through the product's eventual retirement. To develop effective eco-design tools significant challenges must be overcome including the understandings and definitions of fundamental principles for

- conceptualizing the specific information to present to designers,
- presenting such information through intuitive interfaces,
- integrating data from all lifecycle phases back into design tools, and
- developing data sets to foster and validate the above.

Traditionally, LCA tools, for example, are forward-feeding processes where product-specific information is used to generate part-specific LCA results. Relating existing LCA models and results to newly considered part designs remains an open research opportunity [15]. Existing standards for specifying product definitions may be useful in connecting lifecycle data to product designs. Future research can focus on how to leverage emerging technologies for knowledge representation for sustainability-aware design. For instance, efforts could be focused on how to map design features from a computer-aided design (CAD) representation possibly through ontologies [62], to environmental indicators.

Additionally, the intended use of a product from the designer's perspective (i.e., its function) is different from the actual use of the product by the user, including any unforeseen "side effects" (or its behavior) [63]. Hence, it is important to consider new sensing technologies to improve data feedback from the use phase to the design. For example, Ghosh et al. [64] studied how sensors built into runners' shoes can aid in redesign after applying statistical learning techniques to highlight biometric features. Linking user-based field data to design offers potential to aid the sustainable design process.

2.2. ENGINEER MANUFACTURE OF PRODUCT METHODS

The Engineer Manufacture of Product activity addresses the process of making the product, including acquisition of stock materials, equipment, and tooling. The main subactivities for this activity are (1) Determine Manufacturing Methods, (2) Determine Manufacturing Sequences, (3) Engineer New Processes, (4) Develop Tooling Packages, (5) Develop Equipment Instructions, and (6) Finalize Manufacturing Data Package.

Environmentally benign manufacturing falls into two broad categories: (1) developing innovative manufacturing processes for sustainability performance and (2) improving existing processes for environmental performance, including improving manufacturing processes and advanced planning protocols [15]. For this paper, the authors assume that these two classifications cover the first three subactivities from the Engineer Manufacture of Product activity.

2.2.1. Determine Manufacturing Methods

This subactivity defines the major processes involved in making a part and identifies the types of machines that are used.

In practice, comparing manufacturing process alternatives is mostly conducted based on experience or static process-related information from databases, such as CES Selector [51]. A promising method for organizing and retrieving relevant information about manufacturing processes is through ontologies. Some relevant examples include work in distributed manufacturing process planning [65], capability-based process selection for supplier discovery [66], and domain specific ontologies, such as for additive manufacturing [67]. Deploying more complete information models, such as those described in ASTM E3012-16 [21] form, would enable more comprehensive comparisons of environmental impacts related to manufacturing processes and systems [23, 68].

2.2.2. Determine Manufacturing Sequences

The Determine Manufacturing Sequences subactivity defines and validates the sequences of operations that makeup the major processes, including fixturing, setups, batching, fabrication, assembly, and inspection.

One strategy for computer-aided process planning (CAPP) assumes that similar parts require similar process plans, while process plans in other strategies are generated, often automatically by means of decision logic and process knowledge [69]. Challenges remain in the areas of precedence, re-usability, and agility. Precedence specifies the order at which a set of manufacturing processes take place. Re-usability refers to process plans that can be re-purposed to manufacture parts for which they were not designed. Agility describes the system's ability to find good scheduling and planning solutions as process plans change.

Standards play a significant role in sharing knowledge and data across manufacturing enterprises as they become more distributive and collaborative. Current activity in STEP-NC, an effort to integrate product information such as geometric features with manufacturing plans such as machining features, is promising [69]. STEP Tools Inc. provides a series of open-source developer-based frameworks for achieving the integration of manufacturing planning with the design representations, based on STEP [25, 70]. Development toolkits, such as those by STEP Tools, offer designers the potential to develop tools to assess downstream impacts of early decisions in the process planning stages. With regards to sustainability, such tools could help estimate the environmental impacts associated with both manufacturing process choices and manufacturing sequence alternatives.

2.2.3. Engineer New Processes

In this subactivity, if a process is not suitable for producing the part, a new process is engineered. This includes designing new or modified machines, new tools, new measurements, and new process controls. This subactivity also refers to creating novel "green" processes if existing processes are environmentally or socially harmful. Some historical examples include dry machining [71], laser shock peening [72], net shape manufacturing [73], and friction welding [74]. Each example significantly reduced the environmental impact by introducing an innovative manufacturing paradigm. One problem manufacturers face is identifying alternative processes that may be available and evaluating their performance before introducing it into their existing operations. To the authors' knowledge, tools that explicitly support the discovery and exploration of new manufacturing processes do not exist.

2.2.4. Key Takeaways

Accurate and robust manufacturing process models could help populate more accurate lifecycle inventories, which in turn could aid in informing design decisions. Standards for representing such models will help to ensure their completeness, reusablitiy, and integrity. Giving designers knowledge about manufacturing processes and process plans would reduce the uncertainty of forecasting models for sustainability assessment. Several research efforts towards creating environmental models of manufacturing processes for use during product design show promise, including the Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) [75], Reusable Abstractions of Manufacturing Processes (RAMP) [23], and the Unit Process Lifecycle Inventory (UPLCI) [76]; however, they currently remain in the research stage.

Tools for discovering innovative, and more environmentally friendly, processes could be quite valuable. The authors see potential for applying techniques similar to those used by the Materials Genome Initiative (MGI) [77]. The MGI uses standard data representation for materials-related information to employ statistical learning techniques to discover possible opportunities in material discovery. This effort is a multi-national, multi-institutional activity and requires significant funding. A similar effort in the manufacturing process space would require much of the same. To realize such a goal, it would be necessary to merge a large collection of manufacturing-related formalisms. The basic idea being that with the introduction of a large collection of manufacturing data, researchers could employ data-driven techniques, such as similarity metrics [78], to sharpen their focus on manufacturing domains that offer potential towards achieving specific capabilities. One proposed means to organize a large volume of manufacturing data is through general upper ontologies, e.g., the Basic Formal Ontology (BFO) [79]. Interested readers may refer to recent work by Furini et al. [80], which demonstrated using BFO as a foundation for an engineering-related ontology.

2.3. ENGINEER PRODUCTION SYSTEM METHODS

This activity designs new or modified production facilities for a specified part. The subactivities in Engineer Production System are (1) Define Production Engineering Problem, (2) Specify Production and Support Processes, (3) Design Production System, (4) Model and Evaluate System, and (5) Define Implementation Plan. This paper discusses the subactivities of Design Production System and Model and Evaluate System.

2.3.1. Design Production System

During Design Production System, the physical processing systems, material storage and delivery systems, automated control systems and information management systems are designed. This step includes selecting major equipment items, tooling and controllers, and information systems. The facility layout and physical plant requirements are developed and specified.

An important step that contributes to the overall environmental footprint of the product is planning the facility layout. Understanding the production needs of a facility will influence its design and can be used to create energy- and resource-efficient layouts. The Factory Design and Improvement (FDI) model, discussed in Jung et al. [81], describes a systematic approach to use production expectations to design a factory during initial development and to improve a facility during the operational stage. This work is used for facility layout and formulating plant requirements. Centobelli et al. [82] proposed a layout reconfiguration methodology to optimize flow in a plant.

Other research in facility planning has directly accounted for environmental impacts. Despeisse et al. [83] presented a library for connections between general sustainability concepts and specific examples of operational practices in factories. A step-by-step workflow for factory modeling and resource flow analysis is presented and demonstrated via a prototype tool. This provides guidelines for manufacturers for factory modeling, resource flow analysis, and improvement opportunities identification. Paju et al. [84] presented a value stream mapping (VSM)-based assessment for sustainable manufacturing. The Sustainable Manufacturing Mapping (SMM) takes sustainability indicators into consideration and merges VSM, LCA, and Discrete Event Simulation to model process maps. VSM is further extended to Sustainable-VSM [85], which includes metrics to evaluate the environmental and societal sustainability performance of a manufacturing line. Sustainable-VSM presents the performance information visually to assess the performance of the manufacturing line. Yang et al.

[86, 87] presented a facility planning approach that simultaneously considers and minimizes energy, material transport, and manpower costs. The facility layout is generated using a genetic algorithm to solve the objective functions. Furthermore, the tool calculates total costs and evaluates the layout for optimal performance.

2.3.2. Model and Evaluate System

This subactivity uses simulation and actual performance models to analyze the dynamics of the proposed manufacturing system. In this subsection, simulation methods for sustainable analysis of the production system are described in terms of efforts to create reusable frameworks for evaluations and case studies highlighting specific opportunities for improvement. Techniques for monitoring discussed in Produce Product Methods (Sec 2.4) and Control Production (Sec 2.4.2) can be applied for modeling the actual performance of the system.

Various works focus on reusable simulation frameworks that aid in addressing sustainability performance. One standard that addresses simulation of the system is Core Manufacturing Simulation Data (CMSD), which addresses interoperability between simulations and other manufacturing applications [88]. CMSD provides means to define aspects of manufacturing entities that are governed by stochastic processes so information can be exchanged and shared. Thiede et al. [89] discussed commercial software tools and determined that environmental aspects are not sufficiently considered as standard functions. The authors presented directions for future development and research. Kibira et al. [90] present a framework for applying system dynamics modeling to sustainable manufacturing. The methodology was expanded to support interoperability among simulation tools and manufacturing systems that support sustainability [91].

Several industrial case studies have elucidated environmental performance issues for manufacturing facilities. Cataldo et al. [92] modeled and simulated an industrial engine assembly line in SIMIO discrete event simulation platform, focusing on energy consumption aspects. The authors obtained the simulation model of each operating machine by considering mechanical behavior, control parameters, and energy consumption to run a simulation experiment in the simulation platform. This enabled plant designers to evaluate the energy consumption of the conceived plant solution before implementation. Johansson et al. [93] discussed a case study on generating requirements specifications during the early stages of system design through discrete event simulations (DES). The study expands on the SIMTER project, a decision support tool, by using LCI data with DES for manufacturing system design [94]. The SIMTER tool is an interactive system designed using data and models to identify and solve problems regarding environmentally friendly sustainable manufacturing systems. This integrated simulation tool maximizes production efficiency and balances environmental constraints. It incorporates techniques from lean manufacturing, identification and elimination of waste and production losses, and environmental considerations. Diaz-Elsayed et al. [95] created an assessment methodology for simulating, optimizing, and validating a manufacturing systems performance in relation to lean and green strategies.

2.3.3. Key Takeaways

The two techniques used in engineering production system that have the most potential to reduce environmental impacts are optimizing facility layout and simulating performance models for the manufacturing system. Access to more detailed knowledge from this stage enables designers to better understand the layout and planned execution of manufacturing systems. If problems are discovered during modeling and simulation of the system, designers can change designs earlier, without the need for multiple product design change requests. For example, if a product design requires a process plan that uses machines at opposite ends of a facility, requiring a lot of unnecessary movement, time, and energy moving the part from machine to machine, an alternative design that uses a more efficient layout of the manufacturing system might be possible.

An obstacle to enabling downstream feedback mechanisms into product design is the lack of sustainability assessment tools as standard functions in simulation suites. Incorporating these tools into simulation software will enable quicker and more accurate sustainability assessment during simulation. The definition of unit manufacturing process (UMP) models, in the standard format to enable reusability, will reduce the time and effort to build a simulation of the system. By learning from the facility layout through modeling and simulation and by tying this information into design considerations, a designer can lower the overall impact of the product. Accounting for environmental impacts of facility layout during product design is not possible in current practice, but as manufacturing systems become more agile and more accurate data is available to designers this vision is a possibility [96–98]. Achieving this paradigm will require estimates of eco-performance data of the manufacturing line to be presented to the product designer. This data flow is further explained later in the paper through Fig. 5.

2.4. PRODUCE PRODUCT METHODS

This activity describes the steps for providing and maintaining production facilities to produce the parts according to the specifications. Within the activity of Produce Product, the subactivities are (1) Develop Production Plan, (2) Define Production Jobs, (3) Manage Tooling and Materials, (4) Schedule Jobs, (5) Control Production, (6) Manage Production Facilities, and (7) Provide Production Facilities. Interested readers can refer to literature reviews specifically targeted in this area [26, 27]. Another work by Biel et al. [99] presented a review of the state-of-the-art of decision support models that integrate energy aspects into mid-term and short-term production planning of manufacturing companies. For this paper, the authors focus on the activities of Schedule Jobs and Control Production.

2.4.1. Schedule Jobs

The Schedule Jobs subactivity defines the detailed production schedule by managing which workstations will perform what tasks and when they will be performed. One area of research focusing on this stage is energy aware scheduling. Energy aware scheduling integrates energy demand from a facility with production operations requirements to minimize cost and disruptions to the plant. A review of energy aware scheduling is presented in Gahm et al. [100]. A general research framework is developed for energy aware scheduling by analyzing and synthesizing the current state of literature. One method for energy aware scheduling is to selectively switch off non-bottleneck machines for energy savings without sacrificing production throughput [101, 102]. This is similar to the "Shut it Off" method used by GM as described earlier in the paper. Currently, methods exist for calculating the amount of time a machine can be switched off without negatively affecting production. This is called the energy opportunity window [101]. Brundage et al. [102] developed a control methodology using this concept to maximize energy savings with little to no impact on the throughput requirements of the facility. This concept is expanded for intelligent scheduling of maintenance to align with the shut off periods of the machines to reduce energy and provide preventative maintenance [103]. Chen et al. [104] investigated production systems to reduce energy consumption through effective scheduling of machine startup and shutdown.

Other methods for energy aware scheduling focus on total energy consumption, peak load and electric power costs. Legarretaetxebarria et al. [105] discussed scheduling optimization methodologies for energy and time consumption in production lines. The authors set up the energy-optimal scheduling algorithm and the time-optimal scheduling algorithm to obtain schedules by linear programming and bagged binary knapsack. Fang et al. [106] proposed a multi-objective mixed integer linear programming formulation for optimizing an operating schedule that considered peak power load and carbon footprint and obtained an optimal schedule using polynomial-time algorithms. Zhe and Jiang [107] proposed a mathematical programming demand response model with a Mixed Integer Programming (MIP) formulation under real-time pricing. This considered not only electricity consumption of machines, but also electricity consumption of buffers. The optimal schedule obtained by this model results in lower electricity cost and demonstrates improved energy efficiency for the manufacturing system.

Another area of research is integrated production scheduling with heating, ventilating, and air conditioning systems (HVAC) to schedule around electricity demand. By merging the two largest electricity contributors in the plant (the production line and HVAC system), greater energy cost savings can be realized by shifting the energy consumption around periods of high demand. Brundage et al. [108] utilized the energy opportunity window to shift production schedules around high periods of demand for the HVAC system to reduce overall energy impact of the manufacturing system. Dabahneh et al. [109] presented an optimal schedule for manufacturing operation and HVAC temperature to minimize power demand while still meeting production requirements.

2.4.2. Control Production

The Control Production subactivity takes place when the production schedule is implemented to produce the part. The ECOMATION project is used for energy aware control [110]. This tool aims at (1) controlling energy consumption in the manufacturing process and the process peripherals and (2) increasing energy efficiency through automation. Wahren et al. [110] utilized the ECOMATION tool for planning and control to keep the manufacturing system in an energy-optimal state. The tool has several steps to create an energy efficient schedule. First, it selects a production strategy by taking into account the production orders. Next, it creates a machine schedule based on the selected production strategy, and assigns jobs to machines through a scheduling algorithm. Finally, the indicators representing time, quality, cost and energy are displayed in the tool to evaluate and optimize the scheduling. Control Production includes two subactivities: Monitor Performance and Evaluation of Bottlenecks.

2.4.2.1. Monitor Performance

This subactivity monitors performance of processes and line level activities leading to improvements in efficiency and reduction of waste through more consistent processing. Multiple standards address evaluation of the environmental aspects of manufacturing processes. These standards can be used to characterize the environmental performance of processes used in the creation of the part.

At a line level, ISO 20140, Automation systems and integration – Evaluating energy efficiency and other factors of manufacturing systems that influence the environment, provides a framework for the assessment of environmental influence of manufacturing systems [24]. The Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes (ASTM E3012-16) provides manufacturers with an approach to characterize any type of manufacturing process to capture and describe the relevant manufacturing information [21]. The Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes (ASTM E2986-15) provides guidance for evaluating environmental sustainability performance of manufacturing processes [20]. Furthermore, for specific processes, techniques can be implemented to reduce overall environmental impact. These methods are categorized based on the process in Haapala et al. [26].

When evaluating the performance during operations, key performance indicators (KPIs) are utilized to monitor performance. Key Performance Indicators (KPIs) are defined in ISO 22400 as a "quantifiable level of achieving a critical objective" [111] and are used in a continuous improvement strategy to improve performance towards specific goals. To reduce environmental impacts goals and KPIs must be defined to reflect environmental considerations alongside other factors [112–114]. Awareness of manufacturing KPIs could provide critical insight to designers, particularly when used in combination with simulations.

2.4.2.2. Bottlenecks

Another task during this subactivity is identification and mitigation of bottlenecks. Bottleneck analysis identifies and improves a machine that impedes the overall performance of the system [115]. Most bottlenecks refer to a throughput bottleneck, which is the machine that most impedes throughput of the production line. Three techniques used in literature and practice to identify bottleneck machines [116] are identifying the machine that

1. has the smallest isolated production rate (the average number of parts produced by a machine per cycle time),
2. is downstream of the buffer with the largest Work in Progress (WIP) in the system, and
3. has a production rate that most affects the system production rate [117].

Analytical methods [118, 119], simulation based methods [120, 121], and data driven methods [115, 122] for calculating bottleneck machines have been proposed. Simulation based methods can also be used during the Determine Manufacturing Methods subactivity (Section 2.2.1) to identify the bottleneck prior to building the production system. This enables production system designers to allocate resources to bottleneck machines before the system is constructed.

While addressing the throughput bottleneck can help increase throughput of the line, thereby decreasing system resource consumption per part produced, other bottlenecks more directly relate to environmental performance of the system. The downtime-energy bottleneck identifies the machine with the biggest impact on energy consumption per part produced on the line [123]. The rated-power bottleneck is the machine that when replaced with a more energy efficient version will have the largest improvement of energy per part produced on the line [123]. The energy-profit bottleneck studies the trade off between energy consumption and throughput to identify the machine with the highest impact on profit for the manufacturing line [102].

2.4.3. Key Takeaways

The main techniques in the Produce Products activity that impact sustainability analysis are dynamic scheduling of the manufacturing system and monitoring of system performance through environmental key performance indicators and bottleneck identifiers. Schedule information from the Produce Products activity can enable product designers to understand opportunities for energy savings from the manufacturing system. For example, designers can use estimates of eco-impacts of manufacturing schedules to understand how changes in design affect process plans and subsequent schedules in the manufacturing system to better take advantage of the energy opportunity window and energy-efficient scheduling techniques. Also, it might be possible to avoid machines with high impact on the HVAC system energy consumption. Information about energy bottlenecks and machines that are underperforming in relation to their key performance indicators could encourage part designs that do not require the use of these machines during manufacture. More work is needed to reflect these manufacturing performance measures into product designs.

Understanding relationships between sustainability and productivity can enable reduction of costs related to environmental impacts and increase productivity of the facility. Currently, these relationships are not fully understood and future work will examine the correlations between sustainable KPIs (as described in ASTM E3096-17) and productivity KPIs (as described in ISO 22400). This will enable product designers to better understand the impact of design choices on productivity and the environment. Linking these directions with well-established energy management protocol, as described in ISO 50001 [124], could help disseminate these new practices.

3. OBSERVED CHALLENGES & KEY TAKEAWAYS

Figure 3 summarizes Section 2 by roughly classifying all tools and methods according to their level of quanitativeness. Based on the analysis of these tools and methods, some

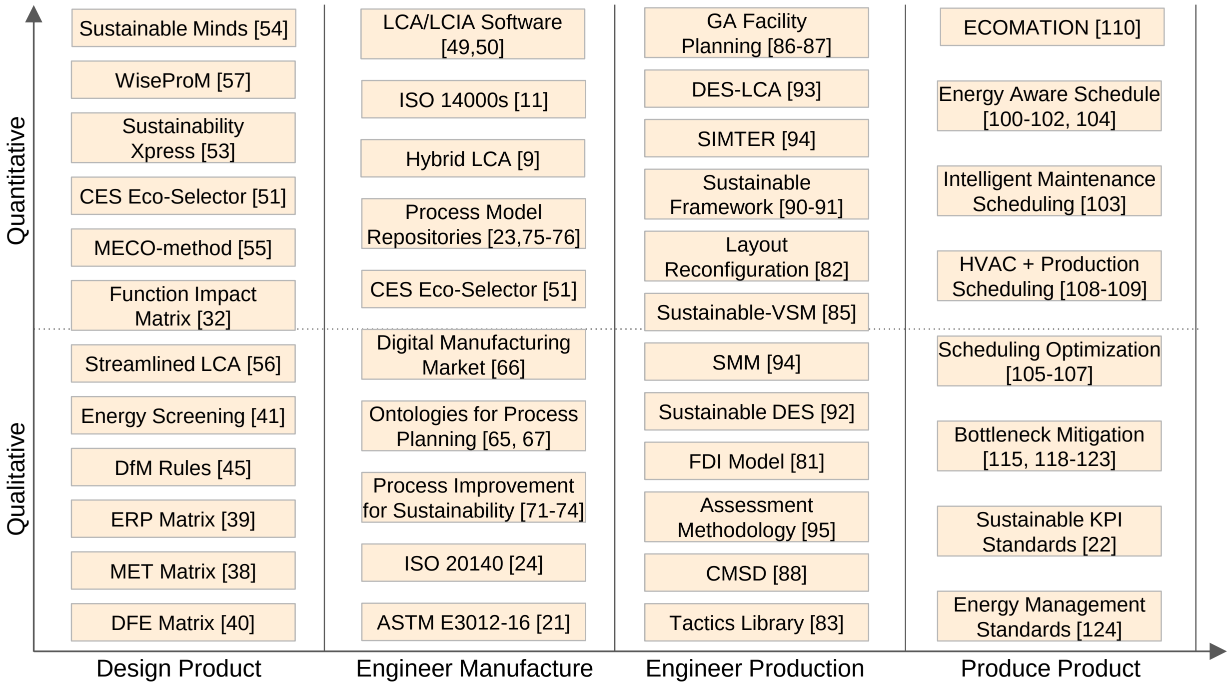

Figure 3: Tools and methods, that were presented in Section 2, classified according to SIMA. Per each column, the tools are ordered from top to bottom roughly based on the prevalence of quantitative analysis vs supporting techniques. Note that this is not an exhaustive list but rather an overview of environmental sustainability-focused methods across the SIMA architecture.

observed challenges and salient themes that cut across the stages of the SIMA architecture are listed. The following observations are leveraged to motivate discussion focusing on recommendations for future work.

- Few out-of-the-box, plug-and-play systems exist enabling data projection to design for sustainable decision making. With the emergence of the Internet of Things (IoT), product-based sensors and other technologies offer potential. However, robust ecosystems for exploiting such available information are still in a nascent stage.
- Formal mappings between information models across lifecycle stages would promote more focused tools. However, no universal agreement on a standard information model that covers the entire product lifecycle exists. PLM-focused standards are generally developed to support specific use cases. Direct mapping between standard information models with different requirements is non-trivial. Overcoming such barriers can be addressed through exploratory research.
- Tools for “streamlining” LCA-based decisions at early stages in the design process would promote more informed decision-making. Such tools exist in CAD packages, e.g. SolidWorks Sustainability Xpress Tool [53]; however, they still lack direct correlation to parametric design attributes, such as those that correspond to geometric dimensioning

and tolerancing (GD&T).

- From a manufacturer's perspective, methods for discovering optimal processes to create more sustainable manufacturing systems are needed. Current research is exploring methods to capture manufacturing knowledge from experienced users and also investigating methods for mining historical data for insights into process performance [125, 126]. Comparing capabilities of manufacturing processes is challenging due to lack of consistent representations across manufacturing domains. For instance, comparing novel additive processes against traditional machining would be difficult. Standard representations for manufacturing processes would provide a basis for comparing disparate processes.
- More flexible manufacturing systems will enable quicker response to spikes in environmental indicators, such as increased material waste. In current practice, the capabilities for data collection in manufacturing environments have far exceeded the ability to apply timely and tangible interventions. Better tools are needed to deliver recommended actions based on diverse data, e.g., maintenance logs in natural language, on-machine controller data, and other data from sensors such as ambient air quality and temperature.
- Similar to detailed design tools, manufacturing process simulation tools are currently disconnected from existing sustainability assessment frameworks, such as LCA software. If this gap is addressed, product designers and process engineers could compare production-related alternatives, such as facility layouts, process selection, and process scheduling, earlier in the design process.

Addressing these challenges requires the integration of standards, tools, and other technologies, such as sensors, publicly available knowledgebases, reusable process models, and maturity models. These tools, technologies, and standards often already exist for many lifecycle stages, but are not fully integrated for information sharing between stages. The authors believe that integrating already existing tools is essential for overcoming the above challenges. This tool integration should also drive future standards in this area. In the next section, the authors discuss future directions to integrate existing tools and construct more useful tools and software for more complete lifecycle analysis.

4. DISCUSSION: TOWARDS BETTER TOOLS FOR SUSTAINABLE LIFECYCLE DECISION MAKING

Improving designers' ability to evaluate tradeoffs to improve the environmental sustainability of products and processes is challenging due to the complexity of the product lifecycle. Sources of complexity include the (1) multi-dimensional nature of the associated metrics, (2) interconnectedness of social and economic influences on sustainability, (3) difficulty in anticipating user behavior, and (4) the disparate forms of associated data.

The following hypothetical situation focuses on the the challenge associated with disparate data across a manufacturing enterprise. Figure 4 illustrates two examples of a

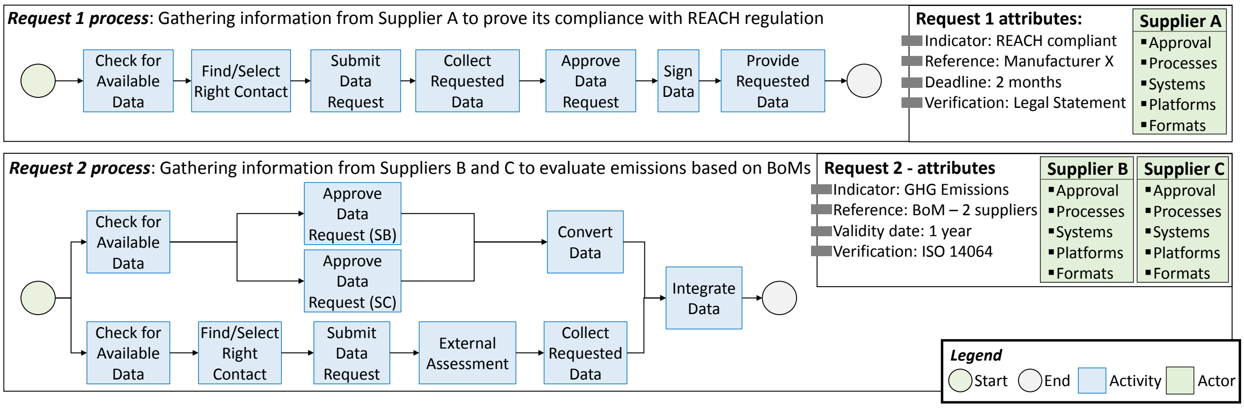

Figure 4: Flowchart demonstrating the complexity in data collection and management for sustainability-related analyses, adapted from Grambow et al. [127].

manufacturer requesting information from its suppliers to report on the environmental performance of a product [127]. The examples highlight the cost of assessing environmental sustainability of complex supply chains in light of even simple design changes. In this example, an OEM communicates with three of its suppliers (namely *Supplier A*, *Supplier B*, and *Supplier C*) to procure information associated with two formal requests for different data. In *Request 1* shown at the top of Figure 4, the manufacturer is tasked to report whether or not a component is REACH[2] compliant. In this scenario, the OEM only must interact with a single supplier, *Supplier A*. However, the process can be time intensive due to the obligation of *Supplier A* to provide a binding legal statement indicating their own compliance. In *Request 2* shown at the bottom of Figure 4, the manufacturer must interact with two suppliers, *Supplier B* and *Supplier C* to procure updated data regarding greenhouse gas (GHG) emissions caused by the production of parts. Simultaneously, the manufacturer must coordinate an external assessment based on ISO 14064 [128]. These examples illustrate the complexity of data collection and environmental assessment even in rather simple requests. These issues are further compounded when attempting to forecast assessments earlier in the product design process due to a lack of data traceability and transparency in downstream supply chains.

To avoid the complexity of data procurement as seen in the example above, knowledge management (KM) tools that leverage historical instances would better equip product and process designers for decision making [129]. The right representation for information across the lifecycle is vital for operationalizing historical data into such tools. Effective KM tools would help stakeholders make environmental-conscious decisions at any point in the product development process, as summarized through the SIMA architecture in this paper.

Figure 5 illustrates the flow of information through the product lifecycle. The solid lines represent potential outputs at each stage. For example the Preliminary Design stage could

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[2] Registration, Evaluation, Authorization and Restriction of Chemicals (REACH)

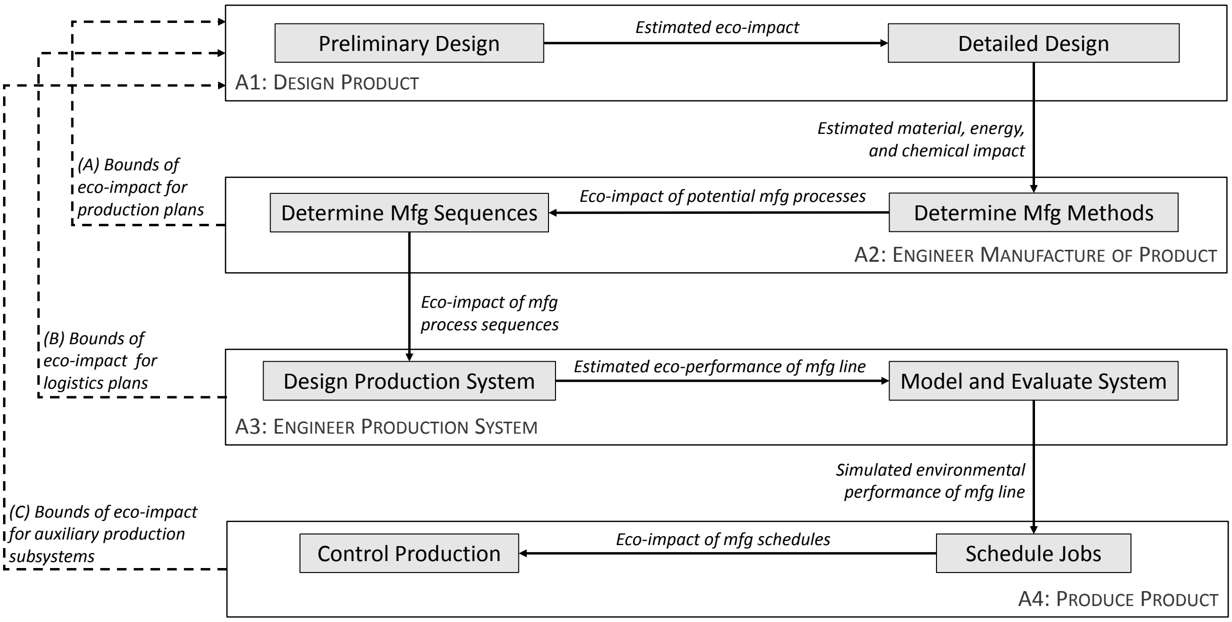

Figure 5: Flowchart of information through the production lifecycle for sustainability analysis. Solid lines represent new information flows between activities in the SIMA architecture to enable better environmental choices. Dashed lines represent potential feedback information that can be relayed to the design stage for better understanding of downstream implications of design choices. The Engineer New Process subactivity is omitted for simplicity.

provide the estimated environmental impact of each of the subsequent stages. The dashed lines represent potential paths of feedback information. For example, after the Engineer Manufacture of Product stage, the potential impact of each production plan could be projected to product designers to make more accurate environmental sustainability decisions. However, feeding downstream information back to design is difficult. This is often due to lack of data formats covering the lifecycle and the lack of influence by manufacturers during part design. The feedback loops in Fig. 5 would lead to smarter product designs when designers have a better understanding of downstream implications of their choices.

Multiple enablers are necessary to successfully incorporate feedback from the downstream SIMA activities. For example, mapping product features to the necessary processes for manufacture will provide more accurate environmental impact information earlier in the lifecycle. Analysis methodologies, such as bottleneck identification, that are agnostic of simulation tools will enable faster and more accurate simulation models of production systems. Reusable UMPs will reduce the time to model processes for simulation, process monitoring, and LCA. Lastly, development of interfaces to display this information to designers is necessary to properly understand environmental impact of design choices.

Lilley [130] classifies these interfaces under “behavior steering” approaches. Behavior steering delivers transparent and understandable data to the decision-maker to encourage more sustainability-aware thinking through its embedded affordances and constraints. However, developing such interfaces comes with its own challenges. According to Rizzoli and Young [131], environmental systems, characterized by the exchanges of energy and material between biological components, present unique challenges due to their unique features, all of which increase the difficulty of developing appropriate and effective tools. These features include

- **Dynamics**: evolves over time.
- **Spatial coverage**: takes place in a three-dimensional world view, e.g., including atmospheric layers, land masses, and water bodies.
- **Complexity**: interacts with multidisciplinary processes.
- **Randomness**: significantly stochastic.
- **Periodicity**: involves data with a variety of time scales.
- **Heterogeneity and scale**: multiple time and space scales.
- **Paucity of information**: data is insufficient in many cases.

These complexities motivate a deeper understanding of designers' thought-processes in sustainability-related decisions. In their sense-making model, Klein et al. [132] present a detailed macro-cognitive model showing a continuous exploration process where the users' frame of reference (or perspective) while assessing data change or evolve based on new information. Such a model can be extended to product data related to environmental sustainability. A number of tools focus on leveraging guiding principles of visual analytics to better inform sustainable design and development [37, 133–138]. Such efforts present a new direction for supporting sustainability-aware decision-making [139]. Additional research to distill design patterns for developing novel interfaces for sustainability assessment are still required. A promising platform, Brightway2 [140], provides a software platform, for expediting such efforts. Brighway2 supports scripted manipulation of LCA-related data and models helping integrate sustainability assessment techniques with state-of-the-art open libraries, such as scikit-learn [141] and D3.js [142]. Kuczenski and Beraha [143] demonstrated the utility of Brightway2 through Antelope, a tool that provides intuitive visualization and interaction with LCA results. At this point, these efforts are research prototypes that have not been fully deployed in a real product development environment. Interested readers can find a list of challenges for visual analytics-based tools within a large company by Sedlmair et al. [144].

5. CONCLUSION & FUTURE WORK

This paper discusses sustainability techniques and methods for evaluating sustainability at different lifecycle stages. The purpose of this research is to identify opportunities where information from downstream stages can help designers conduct more accurate environmental assessments of a product. This enables a more holistic view of the product and can lead to lessened environmental impact. Future work will expand the literature review and perform meta analysis to further discover gaps in the research literature.

In categorizing sustainability techniques, many gaps and barriers impede linking of data from downstream stages to the design stage. Here five fundamental needs of achieving that vision are identified.

1. The most significant challenge relates to sharing information across the product lifecycle. Currently, standards relating to geometry of a part (e.g., ISO 10303) are not integrated with LCA standards (e.g., ISO 14000) and are not integrated with standards for assessing sustainability of manufacturing facilities (e.g., ASTM E3012-16, ASTM E2986-15, ISO 20140). Furthermore, data formats from these standards, such as STEP and ASTM E3012-16, are not compatible with de facto standards for LCA tools (e.g., ecoSpold) due to their differing scopes. Without an integration of these standard formats, it is difficult to create a tool for designers that can accurately assess the environmental impact of manufacturing. Future work will address integration across the standard formats.

2. Another barrier to creating complete assessments of the whole product lifecycle is the time and effort required in building an LCA. Many LCA methods described in this paper are simplified to address this challenge, sacrificing accuracy to spend less time and effort performing the analysis. One way to address this problem is to create reusable UMPs. This would enable designers to reuse models of manufacturing processes created for earlier studies of their products. The models could be reused on many products and be composed with other process models to create full process plans. NIST is currently researching the needs for a repository of process models to address this opportunity [145]. This repository will house unit manufacturing process models written in a format based on ASTM E3012-16.

3. However, even with access to reusable UMPs, a major gap in using these models to create accurate LCAs is that little work exists in automated process planning determining how a change in product design, such as geometry, would affect the process plan. Without an automated tool for environmentally conscious process planning, designers cannot fully understand how their changes would affect manufacturing. For example, changing a product feature might change not only the process necessary to create that feature, but also the order of processes in the overall creation of the product. Tools to understand the effect of product design on manufacturing processes, including process precedence, would enable better evaluation of environmental sustainability when considering design alternatives.

4. Another barrier to more sustainable product designs is the lack of integration between product features and design intent. The lack of this information inhibits the use of more sustainable processing practices. When a feature is added to a product design, the intent of that feature is lost as the product progresses down the lifecycle limiting processing alternatives, perhaps unnecessarily. Similarly, representing design constraints in a standard format to determine how changes to one product feature might affect others is needed. These challenges limit decisions that can be made by

other stakeholders in the process. By linking design intent with product features and accurately representing feature constraints in the design, decision makers can explore alternatives that are more environmentally friendly without negatively affecting functionality of the product.

5. Lastly, presenting the above information in an intuitive and appropriate manner to promote accurate human decision making is critical. Stakeholders in the manufacturing lifecycle have diverse perspectives. As a result, they require multiple views of the data that are consistent with other representations. Future decision support systems should provide the appropriate data to each user for making environmentally efficient improvements to products.

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Disclaimer

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