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Smart and Sustainable Manufacturing Systems

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Manufacturing in a Circular Economy: Research Needs in Design, Systems Modeling, and Digital Thread

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REVIEW PAPER

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ABSTRACT

Momentum is building to transition from a linear (take-make-use-discard) economy into a more circular one in which materials are kept in the economy through value-retention and -recovery processes. This momentum is taking the form of shifts in consumer demand, policies, and business models. As the producer of products and materials, the manufacturing sector is integral to this transition. Voluntary, consensus-based standards are also key to this shift, as they establish foundational terminology; technical guidance in the form of best practices for production; consistent, measurable, and comparable responses to changing consumer demand and regulatory environments; and transparency for consumers and society on product quality and embedded impacts. Despite ongoing momentum, a 2022 survey and workshop led by ASTM Committee E60 on Sustainability found that there was no cohesive, systematic plan for creating the circular economy standards necessary for the manufacturing sector to remain competitive. Results from the survey and workshop were used to develop a roadmap for manufacturing standards across the product life cycle (i.e., from design through production, use, and end of use). Some of these standards are in development now at organizations like ASTM International and the International Organization for Standardization using a consensus-based process; however, many others require new research and development to reach their full potential. This paper identifies three areas, where additional pre-standardization research is needed—design for circularity, system-level modeling and tools, and digital threads—and presents open research questions for future work in each area. Although the research areas are distinct, they collectively require advances in measurement science to enable a systems approach to the circular economy transition; these advances include the development of comparable metrics, standard test methods, and interoperability standards. Advancing research in

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these areas will also help manufacturers assess progress toward circularity goals. This paper aims to inspire researchers to answer these research questions and help create voluntary, consensus-based standards to support circular manufacturing.

Keywords

circular economy, design for circularity, systems modeling, digital thread, standards, research, manufacturing

Introduction

International focus is growing around how to improve resource efficiency and address concerns regarding waste management, supply chain vulnerabilities, and limited resource availability.[1,2] One emerging strategy to address this is to extend and recover the materials already in the economy for continued use—a so-called *circular economy (CE)*.[3–5] In brief, a CE aims to keep products and their materials in the economy at their highest value for as long as possible through design, reuse, repair, remanufacturing, and recycling strategies. On the surface, this approach seems logical and intuitive; however, implementing such a major shift is fraught with challenges. The transition to a CE is introducing new designs, recovery methods, business models, and more; to succeed, each of these new elements should be evaluated based on their ability to alleviate resource scarcity and promote economic resilience. The results of changing practices are hard to predict, much less to verify. Once validated, these strategies rely on new standards to rapidly and safely scale them up.

Manufacturers play a key role in the extraction and production of products in a linear economy and are also vital in the transition to a more CE. In 2022, ASTM International (hereafter, "ASTM") sent out a survey and held a workshop titled "*Fostering a Circular Economy of Manufacturing Materials.*" The workshop itself provided a forum to identify the standards needed to pursue better circularity of materials for manufacturing in the global economy, as documented in the resulting report.[6] To progress global efforts toward circularity, the workshop focused on the interplay between manufacturing, material use and recovery, and sustainability. Although the workshop identified six categories of standards, the participants also agreed that many of those standards would require foundational research developments before they could be realized. Building on these findings, this article identifies cross-disciplinary, pre-standardization research topics and questions across engineering, manufacturing, material science, supply chain, industrial ecology (IE), and operations research (OR). The article describes challenges and opportunities (1) that researchers may consider when planning future research directions and (2) that educators may consider when integrating the concepts at more basic levels into education and workforce curricula.

Rather than focusing solely on existing standards, this article provides a novel perspective by identifying research needs to develop future CE standards. This so-called pre-standardization research identifies and fills gaps in standards, with the goal of helping committees develop and revise standards. Much of the literature on the CE analyzes existing standards,[7,8] their implementation,[9,10] and gaps in the current landscape[11–13]; in contrast, this paper focuses on the research needed to develop voluntary, consensus standards (i.e., standards developed through consensus with relevant parties, compliance with which is neither mandatory nor regulated by the standards bodies) that can help operationalize a CE. Standards development organizations (SDOs)—which create and approve voluntary, consensus standards—operate through committees comprising a balanced mix of stakeholders from industry, government, academia, nonprofits, and consumer groups. These stakeholders rely on their collective expertise and current research to create and maintain standards. Given that a CE encompasses the entire product value chain, SDOs develop standards to cover this broad scope.

Although CE standards are developed by a wide range of stakeholders, this paper targets researchers focused on manufacturing and manufacturing-adjacent fields. Specifically, it discusses how early-stage research can catalyze collective action and convergence on best practices to develop the CE. It bridges the gap between academic inquiry and practical application, offering a roadmap for researchers who want to influence the next generation of standards and support a systems-based transition to manufacturing for circular product life cycles.

The Background: Manufacturing in a Circular Economy section of this article introduces the concept of CE, manufacturing's role in the CE transition, and the methods used for this review article. The Standards for Circular Manufacturing section describes the role of standards in fostering a CE generally, the current standards landscape for the CE and manufacturing, and standards needs going forward. The Research Needs to Advance Circular Manufacturing Standards section highlights research needs to support three pivotal areas for standards: design for circularity, systems modeling and tools, and digital threads. Addressing these research challenges will advance the CE transition by developing the intellectual foundations on which to create new and critical standards.

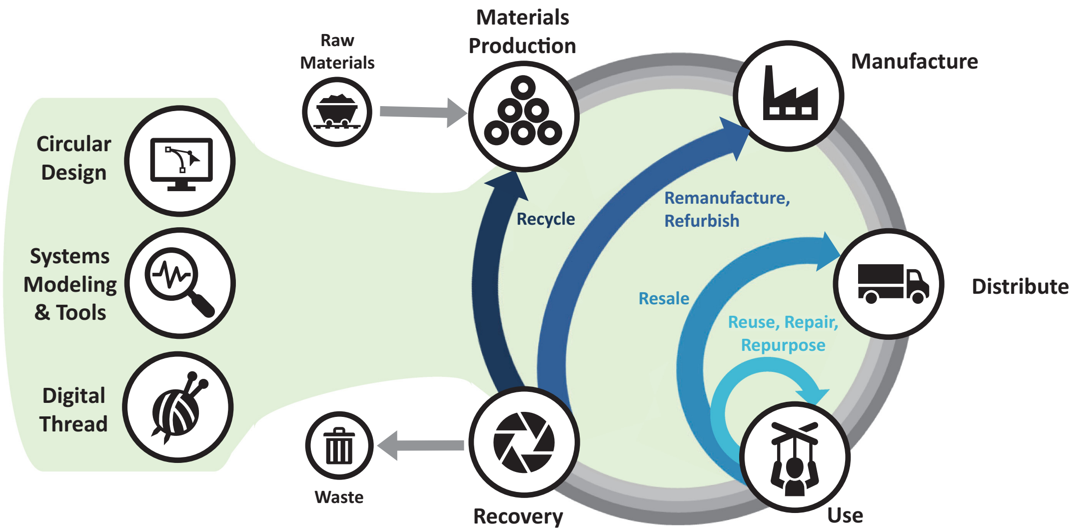
Background: Manufacturing in a CE

Momentum is growing to transition toward a more CE. The public and private sectors are increasingly recognizing the supply chain vulnerabilities associated with the linear economy.[14–16] These risks are compounded by the rising resource demands from a growing global population and a rising middle class in emerging economies.[17,18] Therefore, the transition to a CE is largely driven by the need to decouple economic growth from resource use, and in particular to address challenges of natural resource limitations, waste and pollution generation, and more.[6,19] This decoupling also supports economic resiliency because, as natural resources become scarce, production costs will increase. Thus, a CE is promoted as improving long-term industrial viability and competitiveness because it builds long-term supply chain resilience, strengthens domestic manufacturing, generates business and economic opportunities, and provides environmental and social benefits.[20,21]

A CE model uses a systems approach to keep resources in the economy by recovering, retaining, and adding to their value, thereby contributing to sustainable development.[22] The premise is that, by keeping resources in the economy, more net value is retained. Strategies to accomplish this include processes such as redesign, reuse, refurbishment, and recycling,[22] which broadly aim to prolong product lifespans and recover materials at their end of use (EoU).

Figure 1 shows a conceptual model of a CE. Grey lines depict the flow of materials through a traditional linear economy, while blue arrows display pathways for cycling products and materials back into the economy, thereby extending product lifespans, minimizing waste generation, and reducing demand for virgin materials. Consistent with the waste hierarchy principles,[23] prioritizing the innermost circular pathways retains materials at their highest value for the longest extent possible. International Organization for Standardization (ISO) 59004:2024, *Circular economy — Vocabulary, principles, and guidance for implementation*[22] categorizes circularity pathways into three main loops: narrowing, slowing, and closing the flow of materials. The standard also presents a framework for operationalizing the CE model by defining specific actions, such as reuse, refurbish, cascade, recycle, and recover energy. The ISO standard refers to these as "resource management actions," and this review article bases its definitions for resource management actions on ISO 59004. Recycling is a last resort that should be pursued only after other pathways have been ruled out, such as when a data-driven analysis determines that recycling is the most efficient option for a particular situation. Design plays an integral role in the transition to a CE as it enables each recovery pathway. Products designed for circularity may have increased durability, reusability (e.g., through upgrading), and repairability, and are made from materials that are themselves recoverable and recyclable. The pre-standardization research topics presented in the Research Needs to Advance

FIG. 1 System diagram displaying the flow of materials through the life cycle and the major mechanisms that facilitate a CE. The three areas discussed in this paper—product design, systems modeling, and digital thread—support the development of efficient value retention and recovery pathways across the product life cycle, as represented by the blue arrows in this figure.



Circular Manufacturing Standards section product design, systems modeling, and digital thread—support the CE by helping to facilitate these blue arrow pathways across the product life cycle.

Manufacturers are influential in facilitating the transition to a CE as this sector is at the center of the intricately interconnected relationship between production and consumption, resource use, and environmental stresses.[24–26] Manufacturers drive the market (both supply- and demand-side) for virgin material and the recovery pathways, particularly refurbishment, remanufacture, and recycling. For example, manufacturers can decrease reliance on virgin material supply chains by integrating secondary materials into their operations. Increasing demand for recycled content can create a virtuous cycle by boosting material reclamation, attracting investment into recycling infrastructure, and ultimately driving down costs for manufacturers.[27–29] Historically, manufacturing has operated under the linear model reliant on the continuous extraction of virgin materials. These materials are processed into the building blocks of products, assembled into finished goods, and distributed around the globe with minimal consideration for the life cycle impacts of the product or potential for recovery. Increasingly, manufacturers are transitioning to more resource- and energy-efficient operations across their supply chains and striving to design products with circularity in mind.[30–32]

Collaboration, co-creation, and harmonization are key to implementing circularity.[33,34] CE is a multifaceted and dynamic system that covers the entire product life cycle—from material extraction to EoU—and the systems surrounding the product life cycle (e.g., policy landscapes, business models, and forward and reverse logistics).[35–37] It is very difficult for a single company or entity to maintain its own closed-loop recovery system (i.e., a system in which products and materials are cycled back to make the same products and materials with limited loss of value and function) because it would mean controlling the manufacturing of all associated parts and processes, complex logistics networks, EoU recovery mechanisms, and more. Creating circular solutions requires collaboration to create a baseline for mutual benefit.

The research and standards needs outlined in this review emerged from a 2022 survey and workshop hosted by ASTM. The survey, which was distributed to manufacturers, asked 33 questions regarding firm size, current circularity and sustainability initiatives, and the use of CE- and sustainability-related standards. The 259 survey responses represented firms with global presence; the top industries represented were plastics and rubber, building products, and chemicals. Forty-nine percent represented firms with 500 or more employees, meaning that half of the respondents came from large companies. Survey results were used to inform a virtual, 2-d workshop called "*Fostering a Circular Economy of Manufacturing Materials*" that covered the following topics:

- An overview of manufacturing in a CE.
- Challenges in recycling.
- The use and processing of materials in a CE.
- Circular product and process design.

The workshop converged over 100 experts from different industries and sectors and consisted of presentations and breakout discussion sessions. A report synthesizing the information gathered from the survey responses and the key workshop takeaways was published in 2023.[6] Workshop participants identified standards needs for transitioning manufacturing practices to better participate in a CE (see the Standards Needed to Foster a CE section) and a roadmap for expanding these and developing future standards. A more detailed description of the methods for collecting and synthesizing information from the survey and workshop is available in Schumacher et al[6]

Survey and workshop data were analyzed to identify research needs, which included topics such as product and material traceability, data collection and modeling methods, methods for comparing feedstock materials, and strategies for benchmarking and measuring the impacts of design and process changes. From the analysis, which is detailed in the workshop report,[6] three priority areas were identified for further research:

- Design for circularity.
- Systems modeling and tools.
- Digital threads.

The analysis found that more action in these areas is needed for the manufacturing industry to increase circularity; it also suggested that methods to develop these areas would benefit from collaboration between

FIG. 2 Industry- and academic-driven research addresses foundational questions around which standards are formed. This includes defining the scope and identifying the elements needed to make the standard valuable to all stakeholders ("Guidelines" in the figure). Standards may begin as descriptive (defining current terminology and best practices) and evolve to be more prescriptive (describing specific norms and instructions). As the standards progress in maturity, research can validate the technical consistency of the standards, allowing industry to establish projects, case studies, and pilots based on the standards ("Best Practices" in the figure). These industry actions, in turn, clear the way for the standards to be adopted through, for example, certification programs. Adapted from.[6]

manufacturers and researchers. This article highlights these critical areas and sheds light on some of the open challenges. The solutions need to be researched, demonstrated, and evaluated within the broader communities to ensure that they are effective and relevant. The resulting research creates the social and intellectual capacity to contribute to the technical committees of SDOs, which use it to develop new standards. As **figure 2** shows, research, standards development, and industry adoption work hand-in-hand. Research is necessary to create a mature portfolio of standards that support harmonization and facilitate validation, thus improving industry and market efficiency and consumer trust. As viable solutions emerge, they can be brought forward into the standards processes. This transition from research to standards requires close coordination among the group of stakeholders for the transition to a CE to succeed.

Standards for Circular Manufacturing

Standards are developed based on available information, industry best practices, and the current needs of the sector. They are also updated over time as knowledge and needs change. The technical basis for some of the standardization needs identified by the 2022 ASTM workshop[6] is clear, whereas others will require progress in research, technology, and policy before development can begin. This article outlines research areas that will support the development of standards for a CE. Note that the standards discussed focus on the circular flow of materials broadly and do not cover the numerous standards rooted in specific material types. Creating circular material flows will necessitate new and rigorous standards for material performance, durability, and resilience, as well as new types of materials and associated test methods and specifications.

Standards generally aim to provide harmonized, repeatable, and accepted guidelines, rules, or characteristics for activities or products in a given context.[38] They often provide definitions, technical specifications, or other criteria designed to be used consistently by stakeholders, thus increasing the reliability and effectiveness of goods and services. **Table 1** includes common categories of documentary standards.[39–42]

The development of standards can be initiated at different organizational levels, e.g., international, national, or industry levels. In a consensus-based process, standards are approved by consensus through a recognized body

TABLE 1
Common types of documentary standards

Types of Documentary Standards	Description
Terminology	Contain definitions of terms and explanations of symbols, abbreviations, and acronyms
Guides	Collections of information or series of options that do not recommend specific courses of action. They generally inform people of the knowledge and approaches being taken in given subject areas
Practice methods	Instructions for performing one or more operations that do not generate a test result. Examples include application, assessment, cleaning, collection, preparation, sampling, and training
Classifications	Systematic arrangements or divisions of materials, products, processes, systems, or services into groups based on similar characteristics such as origin, composition, behavior, properties, or use
Specifications	Requirements that must be met by a material, product, process information, system, or service. The specification may identify test methods for determining whether each requirement is met. These requirements can include physical, mechanical, or chemical properties, and safety, quality or performance criteria
Test methods	Defined procedures that generate test results. Examples include identification, measurement, and evaluation of one or more qualities, characteristics, or properties
Reporting metrics	Standard description of what an organization may be reporting on (e.g., global reporting standards)
Codes	Descriptive standards, especially safety-related, that are often adopted into laws (e.g., ASME B31 codes for pressure piping)
SOPs	A description of standard procedures for operations that are based on industry- or company-specific best practices and laws

Note: SOPs = standard operating procedures.

such as ASTM or the ISO.[43–45] These two bodies develop voluntary, consensus standards. However, although voluntary, these standards carry significant weight, as they may be widely and openly adopted across industries; incorporated into contracts and agreements; and used to inform the creation of policies, regulations, and laws. Although organizations like ASTM and ISO develop standards through this type of adoption, users are incentivized to follow the standards, thereby coalescing the results into a robust and cohesive international platform. The standards provide essential technical foundations (from common language to verifiable metrics) for CE principles to be implemented across diverse regions and sectors with consistency and credibility.

As such, the development and adoption of voluntary, consensus-based standards are critical to the transition to a CE, especially for the manufacturing sector. Normalization and harmonization of circular terms, metrics, methods, tools, and practices are needed to reduce risk and support information and data sharing, market stability, and integrity across supply chains and for consumers. The workshop report[6] provides more details on how voluntary, consensus-based standards support CE implementation in manufacturing. However, businesses and governments have not reached consensus on how to interpret circularity, which metrics to use, and how to measure success.[46,47] However, this is beginning to change with the 2024 and 2025 releases of standards in the ISO 59000 series. Standards are therefore needed to harmonize the system, increase transparency and trust among stakeholders and consumers, and support market development.[48,49]

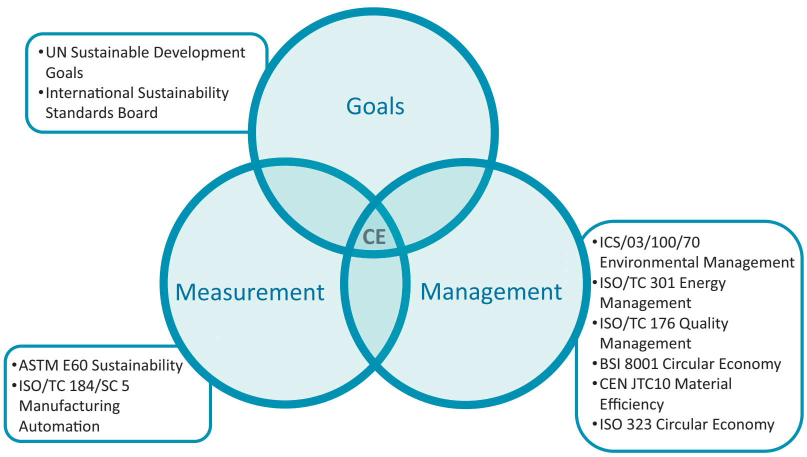
CURRENT CE STANDARDS LANDSCAPE

Existing standards supporting the transition to a CE for manufacturing generally fit into the three categories shown in figure 3.[50] Standards in each of these categories come from different perspectives and often from different stakeholder groups, all working in parallel. Policy experts, managers, and scientists concurrently drive the transition to a CE, and successful transition necessitates that manufacturing organizations adopt new standard practices.

Perhaps the most overarching of existing standardization efforts fit into the category of *goal setting*, which informs and sets the direction for the development of CE standards by facilitating coordination across governments, industries, and investors.[50] Examples include the United Nations Sustainable Development Goals and the International Sustainability Standards Board.[51] *Management standards* create best practices and frameworks for CE standards. ISO, for example, convenes diverse national representatives to create international standards that help bring consistency and quality to management practices worldwide. The ISO Technical Committee 323 on Circular Economy (ISO/TC 323) provides principles and a framework for how to manage and discuss CE globally (e.g., ISO 59004:2024; ISO 59010:2024, *Circular economy — Guidance on the transition of business models and*

FIG. 3

Categories of standards that promote a CE for manufacturing. Adapted from Escoto, Gebrehewot, and Morris.[50]



value networks; and ISO 59020:2024, *Circular economy — Measuring and assessing circularity performance*). Finally, *measurement standards* use measurement science expertise to create documentary standards, specifications, and procedures. An example is the International Electrotechnical Commission (IEC) standard IEC 82474-1:2025, *Material declaration Part 1: General requirements*, which guides users on whether they can make declarations about a material's properties, such as its circularity aspects.[52,53] Transitioning into a CE for manufacturing requires coordination among organizations operating in these three categories of standards.

STANDARDS NEEDED TO FOSTER A CE

Continued and coordinated standards development is needed to build upon the momentum of existing efforts and to address remaining gaps and challenges. Multiple categories of documentary standards are required across the product value chain to support the systems, processes, and infrastructure necessary to retain materials in the economy. The 2022 ASTM workshop identified the standards needed to foster a CE of manufacturing materials and classified them into six categories: (1) foundational, (2) system support, (3) front-end design, (4) manufacturing and production, (5) back-end recovery, and (6) recycling-related standards. Table 2 lists the focus areas for each category, as presented in the workshop report.[6]

Foundational standards are needed to anchor more detailed standards. As ISO prescribes that a CE should contribute to sustainable development,[22] foundational standards include the body of existing standards for assessing the impacts of products across the life cycle. They include standards published by the ISO environmental management committee (ISO/TC 207, *Environmental management*),[54] such as the LCA standards ISO 14040:2006, *Environmental management—LCA—Principles and framework* and ISO 14044:2006, *Environmental management—LCA—Requirements and guidelines*. Although these standards do not focus specifically on circularity, they provide a basis by which to evaluate the results of potential changes that address circularity.

TABLE 2

Categories of standards needed to transition to a CE for manufacturers[a]

Standards Category	Focus Areas
Foundational CE	• Definitions/terminology • Corporate benchmarking and reporting • LCA and inventories
System support	• Systems thinking • Traceability and digital records • Labeling
Front-end design	• Design for circularity (general) • Design for material circularity • Product design for recovery
Manufacturing and production	• Supply chain • Process improvements • Secondary materials marketplace
Back-end recovery	• General • Use, reuse, and repurpose • Repair • Refurbish and remanufacture
Recycling standards	• Collection for recycling • Sorting • Recycling • Recycled content

Note: LCA = life cycle assessment; [a] Adapted from fostering a CE of manufacturing materials workshop report[6]

Foundational standards focused specifically on circularity include consensus around definitions for key terms like "CE" and "closed loop" and best practices for reporting progress toward a CE. Foundational standards set a baseline for a common language and expectations for manufacturers and relevant stakeholders (e.g., governments and consumers) to plan for and address the topic of circularity. At the time of the workshop, ISO/TC 323 was in the process of developing a new series of standards focused on the CE. In 2024, ISO published ISO 59004, an international standard with CE terminology and general guidance on how to implement it, as a foundational standard.[22]

System support standards, on the other hand, are vital for ensuring interoperability and establishing a common framework across disparate systems. Keeping materials in the economy requires strong data interoperability (ensuring that data can seamlessly be exchanged) and traceability across the product life cycle. This includes data on, for example, point of origin, history of the product/material, product design, and suitable recovery pathways based on design. ISO 59010 and ISO 59020 are examples of system support standards because they show manufacturers what value networks and business models are appropriate for a CE and how to measure the circularity of a system, respectively.[55,56]

Next are the standards needed to support the product life cycle, starting with the *front-end design standards*. Decisions made during the design phase have far-reaching implications for other life cycle stages, such as how long the product is intended to be used and how easy it is to implement recovery processes (e.g., reuse, repair, and recycling). "Design for Circularity (general)" includes design principles and guidance that are relevant across the product life cycle. It addresses how design choices both influence and are influenced by systems such as business models, legislation, and market trends. "Design for Material Circularity" and "Product Design for Recovery," however, focus on how design decisions affect material acquisition and EoU.

Standards are also needed to facilitate circularity during *manufacturing and production*. Manufacturers have long worked to improve process efficiency, but in a CE, manufacturers will also address material and energy inputs from their supply chains. Circular product practices will strive to find optimal secondary uses for byproducts, intentionally avoiding landfills or incinerators. The ASTM workshop identified supply chains, process improvements, and secondary material marketplaces as categories in need of CE standards. Additionally, manufacturing and production may have a prominent role in the creation and assembly of relevant product-specific data that can be used during the future recovery phase of products at the end of their use.

The ASTM workshop and survey also emphasized the need for standards that facilitate product recovery, thereby extending useful lifespans and maximizing material reclamation at the EoU. Two categories of standards were identified to address this area: back-end recovery and recycling.[6] *Back-end recovery* is an umbrella term for the different material recovery strategies; *recycling standards* support the collection and sorting of recyclable goods and the process of recycling itself. Recycling standards also include best practices for recycled content, both how to measure recycled content and how to ensure that its quality and performance satisfy the needs of the product it is going back into.

Efforts are currently underway to fulfill some of these standards needs. ISO/TC 323, which comprises representative experts from 83 different countries, has produced a suite of CE standards including those aforementioned on terminology and principles, measurements for assessing circularity, and more. As of March 2026, ISO/TC 323 has published four standards (ISO 59004, ISO 59010, ISO 59020, and ISO 59040:2025, *Circular economy — Product circularity data sheet*) and two technical reports. In addition, in 2025, ASTM Committee E60 published ASTM E3461-26, *Standard Guide for Principles of Circular Product Design*, which begins to address gaps in the *front-end design standards* category by outlining design-for-circularity considerations for product designers, including how these decisions influence circularity in manufacturing.[57]

However, although some CE standards are being developed, further research is required to make these areas more robust and to develop the other standards as outlined in this section. SDOs rely on both agreement among members and scientific consensus. These SDOs collate existing science rather than doing research themselves, making pre-standardization research critical. The following section describes three critical areas, where more pre-standardization research is needed to enable the development of circular manufacturing standards.

Research Needs to Advance Circular Manufacturing Standards

Research challenges limit the development of several standards essential for supporting manufacturing in a CE. Fundamental challenges are particularly prominent in several areas integral to circular systems, including design for circularity, system-level modeling and tools, and digital threads. This section explores each of these areas, touching on the role of each in facilitating a CE, as well as some open research questions that should be addressed to advance standards development. These areas are presented to motivate researchers across multiple scientific disciplines to initiate new projects and collaborations or to consider how existing projects can advance CE standards development. The context and research questions may also inspire students and early-career researchers looking for emerging areas to study.

DESIGN FOR CIRCULARITY

Design choices can have strong, lasting impacts on the types, timing, and volume of materials and products flowing through an economy. In addition, relatively small changes in a product's characteristics often have a disproportionately large impact on material recovery efficiency and subsequent reuse value. Although efforts to recover materials at the end of a product's useful life exist and are gaining traction for specific products, other efforts to broadly recover materials are inhibited by design-stage decisions.[58] For example, choices such as the use of mixed material types for beverage containers, coatings and liners on cardboard boxes, or full-package wraps or labels can make very simple products harder to recover and to retain the highest value for the constituent materials. These problems are magnified for more complex and higher-value products (e.g., appliances, cell phones, and automobiles).[59] Design for circularity means designing products that can both retain and recover value in a CE and integrate used components (e.g., recycled material and refurbished parts).[60]

Scope

Table 3 depicts the three main components of circular product design identified in the ASTM workshop. *Design for circularity (general)* addresses the principles for designing systems, products, and circular business practices in ways that enable companies to operate in a CE. Standards needs in this area include, for example, harmonized principles, measurements, metrics, and criteria to operationalize and track circular design and facilitate circular decision-making. *Design for material circularity* includes decision-making for material selection and processing that enables, or at least does not inhibit, circular pathways. This may include the use of pure materials rather than blends, additives, coatings, or dyes, as well as the inclusion of recycled content in new products. *Design for product recovery* considers the circularity potential of the product as related to recovering value, such as the ability to repair, remanufacture, disassemble, and recover the product and its component material upon EoU.

TABLE 3
Design for circularity subcategories (adapted from fostering a CE of manufacturing materials workshop report[6])

Focus	Description
Design for circularity (general)	Parameterize circular design criteria and operationalize value recovery in design. Incorporate tools such as LCA into design to help assess the broader impacts of circularity potential and measure system-level trade-offs. Furthermore, design for circularity considers pathways to extend service life, avoid emotional obsolescence, and plan for recovery
Design for material circularity	Design materials that are safe for multiple use applications and consider recovery pathways for selected materials
Design for product recovery	Design products that are durable yet capable of disassembly, repair, remanufacturing, and recycling. Make accessible the parts, tools, and other knowledge necessary for optimal recovery

Standards Needs for Circular Design

Standards containing guidance on designing materials, products, and systems for circularity can promote more circular design practices.[61] Furthermore, integrated design tools, evaluation methods, and feedback loops need to be advanced by relying on standardized measurements and methods as guidance to indicate optimal designs. A previous report from this group describes design standards needs identified by the ASTM survey and workshop.[6] Ultimately, standards of various forms are needed to create products in a CE, measure progress toward CE goals, and balance trade-offs in design. Key areas for standards development in this space include measures and metrics for evaluating circularity such that producers can assess, measure, and compare design decisions and operationalize resource allocation across the life cycle of their product (e.g., prioritize designing for repair and remanufacture over recycling).[22] There is also a need to systematically incorporate modeling tools into the design process (see the Standards Needed to Foster a CE section). Another critical area for standardization is designing products that can incorporate secondary materials. Foundational research is a necessary precursor to develop many of these design standards. For example, available literature lacks consensus on circular guidelines, terminology, and evaluation methods.[62,63] The following subsections discuss some of the challenges and open research topics necessary to implement design for circularity in the industry.

Challenges and Open Research Questions

To develop effective standards for implementing and operationalizing circular design, several core challenges need to be studied. Table 4 outlines key research questions that face design for circularity; the questions are discussed hereafter.

(1) *How can designers measure trade-offs when designing for circularity?*

Some design for circularity principles are complementary, whereas others conflict. For example, mobile electronic products like phones and tablets are designed for functionality and durability, often at the expense of repair, remanufacturing, and recycling.[62] Similarly, in the apparel sector, outdoor garments such as jackets are designed with integrated durable fasteners (e.g., zippers) and multilayer fabrics, additives, and coatings to repel water.[63] Although these features extend the life of the product, they ultimately compromise its recoverability. This is a common tradeoff in circular product design between structural durability and ease of disassembly and reducing the number of complex materials used. Research is necessary to understand these trade-offs and what measures, metrics, and models can be developed to guide design for circularity.[47,64] Although general design principles can be useful, it is more useful when descriptive standards like these are followed by more prescriptive standards, such as design principles for specific material and product types. Therefore, research can support both the high-level descriptive standards and more specific prescriptive ones.

(2) *What systems, data, standards, and infrastructure are necessary to build trust in secondary products and recycled materials?*

A CE requires a shift toward more circular materials, including recycled and recyclable materials. However, a key challenge is the lack of producer and consumer trust in the consistency and quality of secondary materials and parts.[65,66] Manufacturers seek methods to better classify secondary materials and components, whereas consumers are hesitant to buy used products and materials because of

TABLE 4
Design for circularity open research questions

Open Research Questions
(1) How can designers measure trade-offs when designing for circularity?
(2) What systems, data, standards, and infrastructure are necessary to build trust in recovered products and recycled materials?
(3) How can products be designed to prioritize the highest value recovery pathways?
(4) What education and workforce training are needed to support design for circularity?

performance and obsolescence concerns.[66] Designers help overcome these issues by better integrating secondary materials into products; clear specifications on material requirements would alleviate these concerns. In addition, improving product and material traceability is crucial, as it enables designers and original equipment manufacturers to access data on the origins, product, and use of secondary materials.[67] Guidance on agile design that accommodates uncertainty in material streams could help stimulate demand for secondary materials.

(3) *How can products be designed to prioritize the highest-value recovery pathways?*

To maximize product and material value, decisions need to be made about the best recovery pathway.[68] Repair, refurbishment, remanufacturing, and recycling have different economic, environmental, and social life cycle impacts depending on factors like remaining product lifetime, available recovery processes, and market conditions. Effective design criteria integrate highest-value circular EoU guidance—e.g., criteria for determining whether a product should be repaired, refurbished, or recycled. Research is needed to (a) determine such criteria, (b) develop methods to improve recovery practices, and (c) incorporate these into the design phase decision making. Tools to effectively measure the impacts of design decisions (e.g., emissions, waste generation, and water use), such as LCA and techno-economic analysis, require evaluation and the development of new approaches.

Product, component, and material degradation are also critical for design for circularity, especially when planning for EoU activities during the design stage.[69,70] For example, if a product, component, or material is to be recovered, the next user must clearly understand its expected performance. Advancements in testing and specification need to be made to assess and convey product and component function and material performance for multiple use stages. The lack of standardized methods to measure and qualify degradation can lead to uncertainty regarding resource recoverability, resulting in missed opportunities for higher-value recovery and incorporation into design. To overcome this uncertainty, product design and recovery standards must be grounded in manufacturing realities; for example, processes should define the feedstock input specifications and allowed contamination rates that will yield high-value reclaimed material and make that information available to designers.

(4) *What education and workforce training are needed to support design for circularity?*

Education is also vital for implementing design for circularity.[71] These concepts and knowledge are novel, and on-the-job training is limited for newcomers to the field. A concerted effort from academia, industry, and other stakeholders, such as standards developers, is needed to develop educational resources for CE-related roles.[72] Particularly, the next generation of designers needs training on broader skills beyond the traditional product designer scope, like adapting and influencing circular business models.[36,71] One way to integrate circularity concepts is by explicitly tying design for circularity into existing operational manufacturing roles, such as training product design engineers to systematically assess whether a material is compatible with existing EoU pathways before adding it to a product.

Yet, although recent standards[22,57] provide much-needed foundations for educational resources, like terminology and general principles, more research and tools are needed to help designers incorporate design for circularity in actionable ways.[73–75] In addition to the industry-focused design for circularity guidelines (that are key to the development of workforce training level content), a recent study[71] also presented broader "themes" underlying these design for circularity concepts that can be especially useful in teaching and creating educational resources for undergraduate education and workforce development.

SYSTEM-LEVEL MODELING AND TOOLS

System-level modeling can help address some of the design-for-circularity challenges, such as improving recovery networks and creating circularity metrics. This modeling addresses the flow of materials in a CE to understand which recovery strategies work best in which instances and how to anticipate the resulting material flows that will support the establishment of economically viable secondary markets. Secondary markets for secondary materials can be developed through cooperation among a number of stakeholders via effective physical and information flows.[76] The CE model is a preventative framework that aims to ensure resource availability for future generations and eliminate the environmental impacts of resource extraction and disposal (see the Background: Manufacturing in a Circular Economy section). In the context of product manufacturing, this is particularly challenging because it requires anticipating evolving conditions and capturing nonlinearities within the manufacturing systems. Research to model the impacts of manufacturing systems relies on accurate and high-quality data related to market dynamics and material flow. Stakeholders must also have consistent access to these data within the defined system. Such data are not readily available; they must be determined through various means (e.g., empirical data collection and statistical forecasts) and must account for uncertainty. Systems modeling tools aim to allow for the consideration of multiple factors and resulting trade-offs concurrently, which in turn leads to the development of metrics and indicators as guidelines to implement suitable CE practices.

Scope

The literature on system-level modeling for a CE has focused on CE metrics and their various qualitative and quantitative applications. Various CE metrics have been developed to understand the environmental, economic, and social dimensions of a CE.[77,78] The current body of work on measuring CE is restricted to metrics development, metrics selection, and the evaluation of certain facets within a CE. Specifically, extensive literature focuses on technological interventions that support product recovery and tracking physical material flows; however, these studies fail to capture the impact of changing product design, evolving market dynamics, and legislation. In short, manufacturing in a CE requires systems thinking.[24,79] Recognizing the limitations in previous work around capturing system-level CE performance, Walzberg et al.[64] proposed that sustainability assessment needs to focus on developing robust methods that capture dynamic changes within a manufacturing system as opposed to isolated and static CE metrics. Their analysis indicates that further research is needed to develop CE assessment methods based on a holistic approach that includes all the dimensions of sustainability (environmental, economic, and societal), thereby considering product life cycle stages. Unfortunately, the current lack of information prevents the implementation of comprehensive circularity strategies. Overcoming this fundamental barrier requires modeling tools that account for changes in market conditions, consumer behavior, product design, and technological interventions.[64,80]

Broadly, the areas of IE and complex systems (CS) have been used to understand the impacts of implementing circularity strategies in the context of manufacturing and products.[64,81] IE is a field of study that analyzes the interactions between society, the economy, and the natural environment. This includes analyzing the flows of material and energy through industrial systems and using them in a way inspired by the efficient and interconnected nature of natural ecosystems. Along with creating efficient industrial processes, IE supports the development of resilient systems and works toward keeping materials in the economy and out of unwanted sinks, a fundamental principle of a CE. LCA, material flow analysis (MFA), and environmentally extended input–output (EEIO) models are IE methods being used to support the transition to a CE (**Table 5**).[82]

A CE can be modeled as a complex system comprising several components in the form of numerous subsystems with multiple stakeholders (e.g., firms, consumers, governments, and NGOs). As such, a CS Science (CSS) approach to the CE can allow several factors to be considered concurrently. Unlike most other scientific fields, where the focus is on individual components within a system, CSS focuses on how components within a system interact and are interrelated. There may be differences among individual parts of a system, and a CSS approach investigates these differences and how they contribute to the system as a whole.[83]

Simulation models can be important for evaluating CS. This is because the use of simulation approaches aims to analyze changes within a system, including anticipating its future behavior.[84] According to Sassanelli, Rosa, and Terzi,[84] the most commonly used simulation approaches are system dynamics, discrete event simulation, and agent-based models.

Another CSS method, OR, includes analytical problem-solving and decision-making methods. Recent research has explored using multi-criteria decision-making (MCDM) models—e.g., utility function-based methods, outranking methods, and programming methods—to apply OR to the CE.[85] OR can also be employed for multi-objective optimization, as exemplified by Mathur, Singh, and Sutherland in their work assessing the environmental and economic impacts of applying life cycle symbiosis to solar panel systems.[79] Further, a CE is collaborative, and research on game theory, another branch of OR, could help practitioners of systems assessments

TABLE 5

IE methods and their strengths and limitations in the context of transitioning to a CE

Tool	Description	Limitations
LCA	• Quantifies environmental impacts of products • Provides a systematic analysis of environmental impacts across every stage of a product's life cycle. By identifying "hotspots," this method helps developers to evaluate trade-offs and make informed decisions to minimize the overall product environmental footprint[131,132] • ISO 14040 and ISO 14044 standardize an internationally recognized, four-stage method: goal and scope definition, inventory analysis, impact assessment, and interpretation. This method assesses the environmental implications of products and processes and can be used across a variety of industry sectors	• Extremely data intensive • LCI data are disparate and need harmonization (e.g., based on geographic locations and data collection methods) • LCA is a static and linear model and does not account for temporal changes
MFA	• Practitioners analyze a system's physical material inputs and outputs, making it a useful accounting tool for measuring stocks and flows • Rooted in the scientific principles of systems approach and mass balance • Can be applied to study physical flows across industry sectors, ecosystems, or regions • Helps increase the efficiency of resource use, minimize waste, and anticipate supply chain risks[133]	• Extremely data intensive, making it difficult to yield reliable results[134] • Although MFAs track the quantities of specific stocks, they do not capture the composition or quality of the stocks
EEIO analysis	• Quantifies direct/indirect environmental impacts of products and services based on economic data[135] • EEIO analyses can be constructed using national statistics and industries' trading information and their respective resulting emissions and resource consumption data • Practitioners do not need to define system boundaries, since EEIO analysis captures details on monetary transactions within an economy	• Lack of data on the informal industrial sector's performance, since these statistics are rarely well-recorded[64]

Note: LCA = life cycle assessment; LCI = life cycle inventory; MFA = material flow analysis; EEIO = environmentally extended input-output.

isolate conditions and factors favoring cooperation among CE actors (e.g., to implement industrial and/or life cycle symbiosis).[86] Tan and Guo[87] also used game theory to determine the impacts of regulations to enable two-way logistics and improve recycling and remanufacturing outcomes.

Although the body of literature that explores integrated models to evaluate CE practices and systems continues to grow, the authors came across limited work on applying these integrated models to track progress toward CE goals.[64,88–90] More research is needed on how to define a system in a CE and which metrics are most appropriate for evaluating a CE—i.e., what to measure and how to measure it. Integrated models that combine IE, CS, and other methods are being viewed as a means to overcome some of the limitations of using individual methodologies. Walzberg et al.[64] provide an overview of instances in which a combination of methods has been used in their recent analysis and note that OR has been combined extensively with other research methods such as IE and CSS. On the other hand, their analysis also revealed that other methods were integrated within their respective fields or used results from other fields—e.g., MCDM often uses results from LCAs in the context of evaluating the environmental impacts across product life cycle stages.[64]

Standards Needs for System-Level Modeling and Tools

The aforementioned system-level tools and modeling methods capture material flows, environmental impacts, trade-offs, and how interventions will impact larger systems. Many of these tools suffer from the limitations of being very data intensive and failing to track the dynamic nature of systems. A CE must overcome these limitations, and standards could help. Standard guides (e.g., modeling approaches), practice methods (e.g., fit-for-purpose data collection methods), classifications (e.g., of material types), reporting metrics (e.g., how many tiers of the textiles supply chain should be reported on), and SOPs (see Table 1) will help organizations effectively collect, use, and govern their data. Standards will also be useful for harmonizing data collected from different sources and in different formats. LCA has a set of commonly used metrics that practitioners use to measure impact across a range of categories (acidification potential, land use, water use, etc.).[91] This gives a standard for both which metric(s) to use for data collection and how to report impact in a way that is comparable. What, however, would a standard metric be for measuring impact and progress toward goals in a CE? Sometimes it is best to capture a system at one point in time, and other times it is important to track system performance and variations over time. Standard guides and operating procedures will inform organizations whether a static or dynamic system will best fit their goals. Capturing a dynamic system is more data intensive than a static one, so these standards will inform organizations about how to allocate resources.

Along with which data are collected and how, standards are needed to facilitate the effective transmission of critical information between processes and among the stakeholders involved. CE is an intrinsically collaborative paradigm, and stakeholders must be prepared to share data that others need to close material loops. However, given the novel opportunities associated with implementing circularity in the context of product manufacturing, questions pertaining to identifying the relevant stakeholders and what their roles are, especially from a CE point of view arise (this is also relevant in the digital thread context; see the Digital Threads section). Standards that enable the identification of key stakeholders and protecting privacy and intellectual property concerns and standards that help define the roles of these stakeholders will be essential to seamlessly adopting CE strategies.

Several of these standards can be initiated now. For example, an international standards organization (e.g., ASTM or ISO) could convene stakeholders to decide if it is possible to agree on a standard unit for measuring material flows generally; if not, then it may be feasible to agree on a standard unit for different industries (e.g., ASTM Committee D20 on Plastics and ASTM Committee D13 on Textiles). Similarly, research is needed to address what other common metrics or methods may be useful to further research around system-level modeling and tools by enabling better foundational data or other means (i.e., measured versus estimated or predicted data). Standards development, like technological evolution or manufacturing improvements, is iterative. Systems analysis and standards development can enable each other, with the potential to create a virtuous cycle.

Challenges and Open Research Questions

Based on the literature reviewed, we identify several open research questions (Table 6). These questions may be especially relevant in supporting the development of standards for the LCA and inventories focus area (Foundational CE) and systems thinking focus area (System support) from Table 2. When addressing these questions, researchers should view the first two as immediate priorities because they cover fundamental metrics and boundary conditions needed to establish baselines. The final three questions represent longer-term goals because they cover how to track and evaluate established systems and integrate them into the broader circular economy.

TABLE 6
System-level modeling and tools open research questions

Open Research Questions
(1) Which metrics are most useful for circular systems, and how can these metrics be standardized?
(2) How should the scope of a system be defined?
(3) How should the dynamic nature of systems be accounted for and modeled?
(4) How do we develop consistent and harmonized product evaluation frameworks in a dynamic system?
(5) What systemic changes are needed to support systems modeling tools for circularity assessments?

(1) *Which metrics are most useful for circular systems, and how can these metrics be standardized?*

A limitation of many of the IE tools in Table 5 is that they are very data intensive. Standards can help reduce the amount of data that need to be collected by clarifying which data the models actually need. More research is needed to determine which metrics are useful for understanding system-level implications of system dynamics; these metrics will help inform the data needs. The industrial symbiosis and CS tools in Table 5 identify one potentially useful set of metrics as the criteria needed to define a system and the system boundary. ISO 14040 and 14044 standards are used to define the system definition and boundaries for LCA. A CE takes a life cycle approach, so these ISO standards may also be applicable to a CE, but research and case studies will help confirm this. Net physical flows, like material and energy inputs and outputs, are another potentially useful set of system-level metrics. Alternatively, in some cases, net monetary flows (like those used in EEIO analysis) may be a better metric for CE systems depending on the scope and goals of the CE systems model.

(2) *How should the scope of a system be defined?*

Implementing circular strategies requires a systems perspective, as closing material loops involves complex interactions. Moreover, representing the dynamic nature of the product life cycle is particularly challenging. This is because the CE relies on both closed- and open-loop recovery of EoU products. This translates to multiple systems, comprising multiple stakeholders and processes interacting with one another. Although methods to analyze CS do exist, a challenge that practitioners often face is defining the system boundary owing to the increasingly CS comprising and interacting with other systems, i.e., Systems of Systems.

(3) *How should the dynamic nature of systems be accounted for and modeled?*

CE is an intrinsically collaborative paradigm. As discussed earlier, CE is facilitated not just by closing material loops but also via the effective transmission of critical information between processes and among the involved stakeholders. However, given the novel opportunities associated with implementing circularity in the context of product manufacturing, questions arise pertaining to identifying the relevant stakeholders and what their roles are especially from a CE point of view. Standards opportunities that enable the identification of key stakeholders and those that help define the roles of these stakeholders are essential in ensuring the seamless adoption of CE strategies.
System dynamics and agent-based modeling are two methods to evaluate systems dynamically[84] (e.g., under evolving market and regulatory conditions). Both are data intensive and rely heavily on market-related data. This requires the accurate collection and recording of data by government agencies, national statistics bodies, etc. A few studies have highlighted the need to develop better data collection methods and models that can accurately forecast future market conditions.[81,92] In the context of CE, this is important to anticipate upcoming material flows and "waste" streams in order to implement the technological interventions and associated infrastructure to enable recovery and close material loops.

(4) *How do we develop consistent and harmonized product evaluation frameworks in a dynamic system?*

Evaluation of product circularity is crucial in a CE. Designers require comprehensive evaluation methods to validate that their design decisions are in fact improving the circularity of a product. In addition, customers require such methods to discover (and demand) more circular products. LCA has long been the most common tool for evaluating product life cycle impacts, yet LCA focuses primarily on environmental aspects (e.g., carbon emissions and water usage). Furthermore, product circularity is a dynamic measure; this is especially the case in a closed-loop system, where factors such as collection rates, virgin feedstock proportions, and EoU resource allocations may constantly be changing.[93] Typical static evaluations such as LCAs are incapable of taking these dynamic variations into account. Therefore, evaluating product circularity requires more comprehensive tools. To standardize the evaluation and representation of product circularity, these fundamental questions can be answered with further research and broader consensus. Such research may also describe the indicators and metrics necessary to measure product circularity, including both triple bottom line impacts and resource circularity (e.g., reusability, remanufacturability, and recyclability) aspects.

(5) *What systemic changes are needed to support systems modeling tools for circularity assessments?*

To further facilitate the adoption of system-level modeling tools, certain systemic and infrastructural changes are necessary across our manufacturing landscape. Effectively implementing standards requires adequate technological capabilities, including data generation, recording, and transmission. Therefore, infrastructural developments and additions to enhance data handling are needed. These include strengthening data collection practices to improve accuracy and reduce uncertainty. Additionally, personnel skilling is required to handle and analyze large quantities of data and develop expertise in simulation modeling and scenario analysis.

DIGITAL THREADS

A manufacturing enterprise consists not only of the physical equipment that transforms goods into products but also of the digital systems that manage the flow of goods and materials into, around, and out of the enterprise. These digital systems are connected by a flow of data that also contributes to controlling physical equipment.[94] In a CE, such data may span multiple life cycles of a product, including the production systems, business partnerships, and business drivers. These systems communicate through varying degrees of automation. Although challenges to integrating the systems abound, so do benefits. The concept of a "digital thread" has emerged to describe the digital connectivity that is created to support systems integration. Although not required, basing the digital thread on standards has been shown to be beneficial because it reduces the complexity, thereby making these threads more repeatable, interoperable, and reliable.[95–97] Digital threads have been successfully explored and deployed, particularly in different aspects of product life cycle management (PLM), supply chain management, and cybersecurity.

These unique circularity requirements are intended to benefit society through efficient resource use, but they must be developed carefully to address confidentiality and intellectual property concerns.

The use of standards to provide a foundation for a circular digital thread is being actively pursued within the European Union (EU), with many national and European efforts focused on the topic, having identified 193 standards of interest.[98] Circular digital threads are necessary to connect information about a product across businesses (i.e., manufacturers, supply chains, and recovery practitioners) and life cycle processes. Standards to support the definition of circular digital threads will ease the burden of information sharing, helping supply chain partners establish and integrate their evolving procurement guidelines, share carbon footprint data, and respond to future regulatory and reporting requirements such as digital labeling. Standards-based foundations for digital threads are being laid in digital identity and material declaration and, more broadly, through the evolution of internet technologies, including the Internet of Things (IoT).[99]

Materials, products, and component parts in a CE may circulate through the economy many times and be used in different products, meaning that different data may be tracked at various points in the product life cycle and across the different uses. At the conceptual level, the consensus is that materials and products need to be tracked and traced, but challenges emerge when actually tracking and tracing different product and material types in detail. Understanding which data are fit for a specific purpose can be challenging; research and case studies are needed to better inform these data and digital infrastructure needs. Before the standards unique to a CE can be created, more research is needed to identify what data points or indicators will serve as the common language between different systems, life cycle stages, and partnering organizations and industries, e.g., for the circular digital thread. Additional research is needed to determine how to measure such indicators for real applications. Research is also needed into how to best weave these indicators into a digital thread that is both useful to value chain stakeholders and maintains intellectual property and cybersecurity protections.

Scope

A significant challenge for implementing a CE is understanding the flow of materials and products such that society and economic actors can respond to the movement of these goods to efficiently reintegrate them back into the economy. ISO/TC 323 categorized this reintegration into narrowing, slowing, and closing the loop.[22] Circular digital threads are a key component in providing information on the flow of materials and products.

For instance, although design innovation is a well-established practice, newer products may have capabilities to track data on their use phase to extend their life[100] and/or to optimize the designs for their intended uses. A circular digital thread will assist in pulling together information from the product systems to inform the next generation of designs. Research in this space may uncover opportunities for greater circularity across the economy. The material flows that will inform these decisions must be based on well-defined and high-quality data and indicators, many yet to be defined, that can be integrated and analyzed in novel ways to provide further insight into the circular systems.

The concept of a circular digital thread is relatively new.[101] The scope of digital threads for circularity will be much broader than those already deployed. CE will change the flow of materials throughout the economy and potentially across multiple life cycles of products; it will also require information flows from different product life cycle phases to inform other phases and collectively address the system-level challenges described earlier.[24,76,102] At the most fundamental level, a circular digital thread supports the recovery of materials and goods. The information captured in the digital thread will benefit recovery services by preparing those providers with insights into the products they are receiving, such as the material composition and best practices for disassembly. Other scenarios will drive requirements unique to circular digital threads:

- *Material track and trace*: Circular digital threads must account for material transformations beyond a product's EoU. Unlike traditional digital threads, circular systems may require data provenance to persist, even as materials are recycled and repurposed. This enables accountability and supports claims like recycled content and responsible sourcing, and drives the need for traceability and validation methods like mass balance accounting[103] and improved cybersecurity.[104]
- *Digital security*: Circular applications like repair, reuse, or refurbishment introduce new security challenges. When products are reused or refurbished, leftover user data must be managed, e.g., erasing it to retain user security or retaining it for compliance tracking. For example, electric vehicle batteries and electric vehicle battery management systems may contain data that the manufacturers consider intellectual property. Access to these EoU data can help improve recovery activities. A future digital thread must balance intellectual property protection with secure data sharing. Concerns over data privacy lead to low reuse rates in electronics because device destruction is widely seen as the most secure way to protect data.[105–107]
- *Disassembly guidance*: Although digital threads and circular digital threads in PLM both focus on design and assembly, the latter must also support disassembly to enable repair, reuse, and recovery.[108] Existing PLM-supporting standards may not fully address this need. Further research is needed to identify the requirements and the strategy for integrating solutions into frameworks of existing standards and tools.
- *Predictive market data*: Circular digital threads also offer system-level insights beyond individual products. Aggregating EoU data can inform forecasts of material availability and recovery potentials, supporting strategic planning for infrastructure like reverse logistics and secondary markets. This level of insight can contribute to planning for recovery operations, supporting services, and future supply capacities.[109,110]

One application of a circular digital thread is digital product passports (DPPs).[111] A DPP is a conceptual method for applying a digital identifier associated with a decentralized data system to trace products and materials throughout their life cycle to facilitate data exchange and recovery.[112,113] In theory, DPPs hold enough information to facilitate the recovery of the product through the most efficient pathways. The format and content of DPPs, both in general and in particular, are still loosely defined (i.e., not standardized) and are an area of active research and standards engagement. Specific definitions for DPPs will be based on the needs of the products, supply chains, recovery methods, and the available information sources—in other words, the feasibility of circular digital threads to support the information needs. A DPP definition for a particular product type is, conceptually, the designator of the information requirements, including the events that need to be traced. Circular digital threads are needed to link those requirements back to existing data sources within the participating organizations' digital ecosystems. Standards will streamline and drive circular digital thread definitions, as has been done in the PLM area.[95,114]

The EU intends to require DPPs for a wide range of product types as part of its Ecodesign for sustainable products regulation.[31] Work is underway in the EU with the CircThread Program[102] and the CIRPASS initiative[115] to prepare industries to operationalize DPPs to adhere to the regulation; results from CIRPASS have been published on the DPP system architecture[116] and DPP case studies for batteries, electronics, and textiles.[117] The EU Battery Pass consortium, working to deploy results from this research to satisfy forthcoming EU regulations for batteries, is a model for how these programs will be rolled out.[118] China, too, has launched an initiative to develop a DPP system specifically for electric vehicle batteries to facilitate trade.[119]

Standards Needs for Digital Threads

The digital thread generally is a prime area for more standardization. The approach has been leveraged across many domains such as product definition, production, inspection, supply chain visibility, acquisitions, and product servicing. A digital thread built on standards can help bridge information across different processes in the product life cycle.[95,96,114,120]

A digital thread associates information from a variety of disparate systems. In the case of a DPP, those systems may come from a broad range of stakeholders, including manufacturers and their supply chains, consumers, and recovery practitioners. The information (events and data) is defined by a DPP for a given type of product, and a digital thread is created to provide the information for a DPP system. With standard information representations, a digital thread can be constructed such that, when carried throughout a product's life cycle, it can create a verifiable history of events that have transpired for that product. A useful digital thread requires the following:

- a clear and concise understanding of the processes that benefit from a digital record and the specification of data to be shared,
- the value proposition for creating such a record,
- clear and complete definitions of the information units required to capture the record, and
- methods and formats for representing the information units and sharing that information across the range of stakeholders and systems.

The use of standard formats in the creation of a digital thread enables further expansion of the datasets as more needs are recognized and facilitates the integration of other businesses or information systems into the digital record.

Challenges and Open Research Questions

The ASTM survey and workshop identified a circular digital thread as a high-priority need. However, there was no consensus on the format for such a thread. Given the variety of products and ecosystems in which this thread is made and used, open research challenges include how to identify new circular digital threads and which data formats and technologies to use (several of these challenges are presented in Table 7). Many of the capabilities that a CE hopes to address will rely on sharing information across product life cycles and using information to yield system-level insights into the flow and availability of goods and materials. Overcoming this challenge will require an infrastructure to create and operate circular digital threads that support secure, reliable, and relevant information sharing. Much of the underlying technology will be driven by internet and software providers, but fundamental research challenges still need to be addressed with respect to manufacturing needs.

TABLE 7
Digital threads open research questions

Open Research Questions
(1) Which events in a product life cycle are relevant for CE scenarios?
(2) What are the units of interest for a circular digital thread?
(3) How should data be shared for a circular digital thread?
(4) How should digital threads be tested?

Digital thread research can support standards across the entire product life cycle. However, this research may be especially relevant to creating standards in the traceability and digital records focus area (System support) from Table 2.

(1) *Which events in a product life cycle are relevant for CE scenarios?*

Understanding which product life cycle events are critical for supporting CE goals is essential for developing circular digital threads. These threads rely on data collected periodically (e.g., location, condition, and composition) across the product life cycle, including at customs checks, during maintenance, and at the various recovery stages. Events vary widely by product type, jurisdiction, and point in the value chain. For example, different products are checked for different attributes—organic matter is treated differently from electronics and textile waste—and commercial products entering by trucks or ships are treated differently from those declared by individuals at the airport. Identifying which events and corresponding data units are most relevant requires interdisciplinary expertise and careful cost-benefit evaluation to ensure data collection supports circularity goals.

Determining which product life cycle data (including recovery-stage data) are needed for a variety of product types is challenging and requires a broad range of expertise. In addition, it takes significant effort to (1) identify the data of interest and (2) determine efficient ways to collect and record those data. Research and case studies are needed to determine events appropriate for a circular digital thread. Research can identify the informational units to be collected and seek validation relative to circularity objectives, as well as practicality before consensus standards can be built. Additionally, the cost of collecting, storing, and controlling future access for the data must be shown to justify the efforts in terms of economics and reductions in environmental impacts.

A type of data of particular interest is that related to traceability of the product. Traceability refers to the collection of data at critical points in a product's life cycle. The points at which traceability data are collected are referred to as *traceable events*. Projects such as the EU's CIRPASS[115] and Battery Pass[121] are advancing this work by exploring which events to track and how to implement supporting technologies. ISO's resource management actions[22] and industry consortia[122–125] also provide frameworks that can be leveraged. However, significant opportunities remain to shape these efforts and develop scalable, standards-aligned approaches across diverse product categories.

(2) *What are the units of interest for a circular digital thread?*

Identifying useful units of information for circular digital threads is challenging because relevant product life cycle data come in diverse types, formats, and semantics. Not all data are equally valuable, either; raw IoT data from manufacturing, for example, may only be useful insofar as they inform key performance indicators like machine health or product quality. But which data would be useful later in the life cycle and at what cost? Which data are worth keeping? Determining which indicators are most relevant for circularity, and at what granularity (e.g., batch versus serialized product data), is essential for effective data sharing and decision-making.[97] For instance, the data about material content may be gathered by batch, by time interval, or by individual product. Further study and perhaps a framework for articulating which choice is most appropriate under which circumstances are needed.[103,126]

The information needed to create a circular digital thread may be stored across multiple production systems that operate on different platforms. Efficient methods for collecting it are needed, and these methods may involve new architectural components such as edge computing. Furthermore, new artificial intelligence methods may be leveraged to create digital threads by analyzing the contributing systems and generating mapping code or tools such as knowledge graphs. Other techniques, such as large language models, may have novel applications to overcome this challenge as well. Standards-based ontologies could also play a role in testing or even making sense of resulting integrations. In addition, research in cybersecurity can be applied to the need for role-based data access to protect business-critical information. To address these challenges, strong case studies are needed for a variety of implementation environments, product types, and circularity requirements.

(3) *How should data be shared for a circular digital thread?*

Once information is collected, it will need to be made sharable for stakeholders. Many challenges exist regarding this type of information sharing, such as how and when to pull information and integrate it with existing data systems, and how to represent identity. Different product types will have different systems for identification and different needs in terms of granularity of the data shared. In addition, several strategies being proposed for DPPs are calling for information to be shared only on a "need-to-know" basis and across a federated system of data stores. How can such a strategy be managed and implemented securely, and what are the requirements surrounding ownership and longevity of the information that is collected? Some methods to address these open research questions are still in the research and development stages, like the application of dataspaces and knowledge graphs in dispersed federated environments.[127] In addition, a collection of reference ontologies to facilitate these integrations is under development within the Industrial Ontology Foundry to support connectivity of technical data across dispersed systems.[128,129]

Although the EU is working to define the DPP to regulate a broad range of products, most industries and their stakeholders are concerned with tracking and tracing the products. For example, to address health and safety concerns, the food industry expects traceability to the source of their ingredients. Other industries also seek supply chain traceability to validate social sustainability metrics, such as worker health and safety. Conversely, others want to track where their products and materials end up for a range of reasons, such as material recovery, national security, or brand protection. These broad efforts with similar functions may yield new challenges in establishing a single point of truth.

(4) *How should digital threads be tested?*

Metrics for successful circular digital threads will be critical to testing whether the digital thread is working as intended. These metrics may include how secure the data are, how much uncertainty the system tolerates, whether those that need it have access to the data, and how much data the system requires to operate as needed. These metrics can be standardized by consensus, so they work in an international context to support international value chains. Case studies will also help confirm that these metrics are relevant for different fields and guide users attempting to implement and troubleshoot the thread. In addition, CE scenarios can be examined to explore the role of digital threads in CE and to improve the circularity of a product. This will include the information required to use a product, or its components, past its EoU into a new product life cycle and an understanding of what information on previous product life cycles should be represented going forward. However, to begin to understand the process of testing a circular digital thread, we first need robust case studies to understand the life cycle data required.

Other test criteria must also be explored, like those related to cost-benefit analyses. Specifically, what are the costs and benefits (both environmental and financial) of collecting and maintaining data,[130] and how do we assign these costs? Are the burdens of the costs to be allocated on a product, corporation, or societal basis, and are those burdens apportioned justly? Can these costs be managed? Would judicious selection of data and timing of collection and sharing help? Would the deployment of such a system create another set of unintended and detrimental consequences? Although these costs do not apply to the implementation of a given digital thread, they do apply to the platform on which these threads will be created.

Discussion and Conclusion

Companies and governments around the world are working to transition from linear to circular economies. The manufacturing industry is pivotal to this transition, as it introduces materials and products into the economy and is key to creating the supply chain resilience and effective development that the CE supports. Standards like the ISO 59000 series are being developed, but major gaps remain that are hindering the wider adoption of circular manufacturing. This paper identifies three pre-standardization research areas that can overcome many of these gaps: circular product design, system-level modeling and tools, and digital threads.

Several key threads connect these research areas. First, current modeling tools used to assess CE in manufacturing are limited. We need new modeling tools and improved interoperability between existing tools to overcome the limitations of single tools and create a more comprehensive picture of CE systems. Second, robust metrics and indicators are needed to evaluate circularity across different life cycle processes. These include material flows, social circularity metrics, as well as environmental and economic metrics. Methods are needed to incorporate economic metrics and metrics to compare the economic, environmental, and social performance of a CE against traditional linear models. These metrics are crucial for establishing baselines for CE implementation, tracking progress toward goals, and ensuring that different modeling tools are compatible with one another. Finally, manufacturing systems are dynamic; to be effective, new modeling tools and metrics need to be adaptable, resilient, and flexible enough to accommodate future market developments and technologies.

Despite the growing body of standards and research, the CE transition faces practical barriers, notably the lack of data availability and interoperability across diverse and complex supply chains, as well as significant workforce and skills gaps in designing and managing CS. The research into circular design, modeling tools, and digital threads proposed in this paper can help to overcome the interoperability barriers by creating technical solutions, such as improved digital protocols for data handling and exchange and robust economic modeling tools. These advancements can also be used to create curricula and upskilling programs. Finally, these technical solutions, in turn, can be validated through pilot projects and formalized into standards, thereby enabling widespread and efficient CE implementation.

In conclusion, transforming design and manufacturing practices requires a multi-pronged approach. Prestandardization research plays a vital role in identifying where new standards are needed and ensuring these standards are effective for all stakeholders. Engaging a diverse range of stakeholders, from engineers, designers, manufacturers, and consumers to regulators and environmental experts, throughout the standards development process is critical.

Researchers are uniquely suited to support solutions through case studies and industry engagement. These studies yield results and methods that can then be translated into more generalizable lessons for broader audiences. These lessons can be shared through peer-reviewed publications and presentations. Results can also be brought to standards committees, where stakeholders work together to form consensus toward shared goals. In the case of the CE, a number of standards organizations are doing this work. For example, ISO/TC 323 is currently examining metrics and measurements for circularity indicators, whereas ASTM is working toward standards for circular design, including for medical devices and plastics, among others.

Along with researchers answering the questions presented in this paper, educators can inspire students and the existing workforce to engage with this new frontier. By fostering collaboration and incorporating various perspectives, we can create robust and adaptable standards that accelerate the transition toward a CE. This collaborative approach, coupled with ongoing research and development, will pave the way for a more resilient and resource-efficient future for the manufacturing industry.

DISCLOSURE OF POTENTIAL CONFLICTS OF INTEREST

The authors report there are no potential conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

No data, models, or code were generated or used for this study.

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