Refocusing the Barriers to Sustainability for Small and Medium-sized Manufacturers

Xavier Escoto[b], Demsas Gebrehewot[b], KC Morris[a]*
[a]*National Institute of Standards and Technology, Gaithersburg, MD, 20899, USA*
[b] *Georgetown University, 3700 O St NW, Washington, DC 20057*
* Corresponding author. *E-mail address:* kcm@nist.gov

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Abstract

Sustainable manufacturing practices are a necessary component of sustainable development. Current practices in a linear economy—produce, consume, discard—will not be sufficient to sustain humanity over the long term. At the same time manufacturing is necessary to support the world's ever-growing population. The efficiencies of scale that manufacturing brings to bear on the global economy allow greater sharing of services and resources. Research and practices supporting sustainable manufacturing are necessary to control impacts on the environment. From an engineering perspective, however, those practices are in their infancy. Small and medium-sized manufacturers (SMM) make up the majority of manufacturing firms globally, but many are still unsure of whether and how to embrace sustainability as a driving business imperative.

In this study, we explore two interconnected approaches to address sustainability: the benefits of investing in sustainability initiatives for SMM and the use of standards to support such initiatives. In so doing, we analyze reported barriers to SMM pursuing sustainability, the value gained from sustainability-focused operational improvements within SMM, and the benefits of grounding those improvements in standards. The results indicate that 1) reported beliefs surrounding the benefits of pursuing sustainability goals should be refocused in light of the data on business performance and 2) standards developments is foundational to pursuing such objectives. This study examines multiple data sources to reach these conclusions, including open literature, expert interviews, corporate sustainability reports, and performance data across multiple years from programs supporting SMM in improving sustainability performance.

The study reviews the role that different standards fill and highlights those that are instrumental in pursuing manufacturing sustainability objectives. While several standards from the business world have emerged to establish industry-specific sustainability disclosures, little guidance is available to manufacturers on how to implement and show improvements to their practices. Recently, the Sustainability Accounting Standards Board (SASB) produced standards to target sustainability goals in specific industrial sectors. Other standards bodies, including ASTM International's E60 Committee on Sustainability and Subcommittee on Sustainable Manufacturing (E60.13), specifically address practical guidance for manufacturing operations in the form of standards. The intent of such standards setting bodies is to make manufacturing more sustainable, yet the organizations have evolved independently. Consequently, their respective standards reflect different types of measures based on the distinct users' perspectives. These and other standards efforts are highlighted as supporting the integration of sustainability goals into manufacturing organizations. These findings demonstrate that (1) integrating sustainability as a business imperative, particularly by SMM, can (1) result in business opportunities and (2) leveraging standards reduces the risk of introducing changes. Future efforts towards more sustainable development can be furthered through the development of voluntary standards for implementing new operational approaches. Such standards can help to engage more SMM in sustainable development by reducing the risk of introducing changes into their existing practices.

Keywords: sustainability, manufacturing, standards, ISO, ASTM International

1. Introduction

In recent years, several efforts towards creating accounting standards for sustainability have emerged, and manufacturers are struggling for ways to achieve and report progress (Oxford Analytica 2021). While large corporations do file reports, those reports are non-standard, making them difficult to compare. It is particularly challenging for Small and Medium Manufacturers (SMM) to produce such reports, and many SMM are not motivated to undergo this challenge (Pucker 2021). Standards are needed to ensure consistent and reliable reports, but the lack of organization in the standards, metrics, and systems related to the sustainable manufacturing practices has resulted in uncertainty around how to proceed among practitioners who seek to create positive impact within their organizations. This lack of clarity is especially significant for SMM as larger firms attempt to engage supply chains when reporting on sustainability efforts. More engagement by SMM towards sustainability objectives presents an opportunity both for individual firms and for greater societal progress towards sustainable development goals. In the United States (U.S.), for example, SMM make up more than 98% of the manufacturing firms and account for 76.6% of the manufacturing sector's total environmental impact (Bureau of Labor Statistics n.d.) (Thomas 2020). The purpose of the present study is to examine roadblocks to achieving sustainable manufacturing objectives and to identify a path forward, particularly for SMM.

The approaches from large stakeholder communities differ because they address sustainability issues from individual points of view as shown in Figure 1. Life cycle thinking highlights the full impact of a product on its environment in all phases of its life, from material extraction, composition and sourcing through the use phase of the product to end-of-life disposal or reclamation. The International Organization for Standardization (ISO) 14040 series of standards on Life Cycle Analysis (LCA) quantifies life cycle impacts. LCA is the most developed approach for measuring a product's impact on the environment, but has limited applicability for improving the manufacturing phase of the product life cycle when the product design has already been already determined. LCA is also limited by the availability of accurate input data from the various activities contributing to the product life cycle, especially from the manufacturing phase. Sustainability impacts during manufacturing can vary drastically based on the combinations of product design, manufacturing process, and material selection; optimizing these combinations can reduce impacts and add value.

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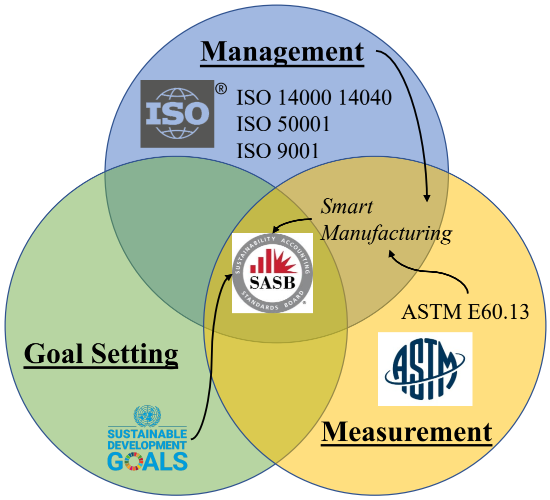

Figure 1: Standards and Technology Trends

Figure 1 shows different categories of standards that overlap to form a holistic approach to addressing sustainable development. Note that the standards mentioned here are only examples of standards in each category that are needed to facilitate sustainable development. The figure identifies three categories:

- Goal Setting—helps define the overarching objectives,
- Management standards—establish best practices towards objectives and common frameworks, and
- Measurement standards—provide precision and comparability in moving towards objectives and enabling technological advances.

Other standards have been successfully employed to improve the manufacturing phase, and more are emerging. Figure 2 shows a timeline for the development of suites of standards discussed here that will enable more sustainable manufacturing. A collection of ISO management standards have been shown to improve sustainability for manufacturers, in addition to other goals. This collection includes ISO 9001 for quality management, which helps reduce scrap and waste by establishing tighter control over processes; the ISO 14000 series on environmental management, which defines practices for establishing an environmental management system; and ISO 50001 on energy management (Naden 2020; Lyndenberg and Wood 2010). These standards stop short of providing specific technical guidance for manufacturers to determine how to collect information on their own impacts. Standards from ASTM International's Subcommittee E60.13 on Sustainable Manufacturing provide technical guidance, emphasizing an approach to process improvement that allows manufacturers to set their own sustainability objectives based on their business constraints. While still limited, the initial set of ASTM standards lays a foundation for expanding into several areas. They address process improvement, economic analysis, and material disposal. In addition, the Sustainability Accounting Standards Board (SASB) effort from the investment community has a significant manufacturing component and provides guidance to prioritize sustainability efforts within an organization based on the enterprise's core business functions. This approach, which consists of reporting standards across 77 industry sectors, informs the use of an organization's resources to affect activities that are financially significant to the enterprise.

The innovative aspects of this study are to deconstruct the barriers and highlight the role that standards can play in pursuing an organization's sustainability objectives. This study addresses fundamental questions for pursuing sustainable manufacturing objectives for SMM: What are the barriers to SMM pursuing more sustainable practices? Are those barriers reinforced by experiential data? Which standards and technologies are available and emerging that will foster more sustainable practices in manufacturing? This study examines two interconnected approaches to reducing the sustainability impact for SMM in light of barriers to sustainability

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that have been reported in the open literature: (1) using standards to implement continuous improvement methods and (2) using investments in technologies to address sustainability goals. Section 2 provides background on the motivations for manufacturers to adopt sustainability practices and introduces SASB and its role in highlighting financial materiality within sustainability efforts in manufacturing organizations. It also examines the extensibility of industry-wide trends to SMM and the reported barriers to sustainability. Section 3 describes our methodology for examining the reported barriers to sustainability, the process we employ to refocus these barriers, and how to ultimately assess the success of SMM within the context of those barriers. Section 4 examines the barriers in-depth and highlights findings from successful sustainable manufacturing efforts. It provides a review of the sustainable efforts from several key industrial sources—corporate sustainability reports from multinational corporations that have elected to disclose SASB data, industry practitioners, and two key federal programs that partner with SMM on sustainability efforts. The section demonstrates that sustainability efforts can have observable financial benefits to SMM and challenges manufacturers to revisit the reported barriers using these new insights. Section 5 follows with a discussion of key technologies and standards that have demonstrated the potential to guide sustainability initiatives towards positive results, while being mindful of the reported barriers. The study concludes with emerging standards efforts that can be harnessed to make sustainable manufacturing more achievable for SMM.

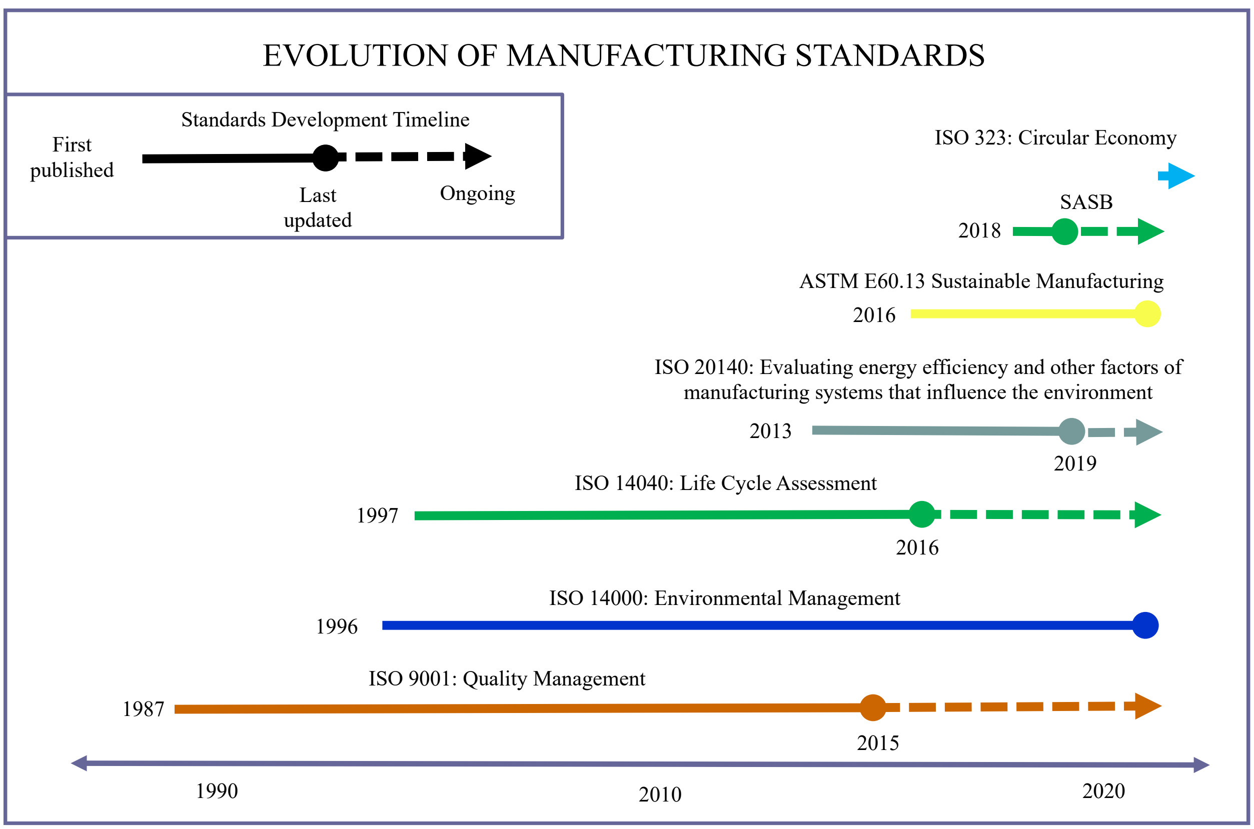

Figure 2 Timeline of standard development for enabling sustainable manufacturing

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2. Background

According to the Organization for Economic Cooperation and Development (OECD), sustainable manufacturing refers to the ability to manage manufacturing operations "in an environmentally and socially responsible manner" (Organisation for Economic Co-operation and Development 2021). Sustainable manufacturing has been a subject of on-going research as society looks for ways to improve manufacturing practices to protect people and the environment while continuing to operate financially viable businesses. Writing in 2012, Despeisse et al. (2012) analyzed work in sustainable manufacturing across several industry sectors to identify key themes around sustainability; they pointed to an area in the 1990s labeled "environmentally conscious manufacturing" as some of the earliest work on sustainable manufacturing research. In 2011 NIST created a repository of Sustainable Manufacturing Indicators to consolidate the disparate efforts of several organizations to define sustainable manufacturing in terms of what is measured (Joung et al., 2013; Sarkar et al., 2012). In 2015 the United Nations adopted 17 Sustainable Development Goals in their *2030 Agenda for Sustainable Development*; three specifically address manufacturing practices (United Nations 2015). In 2020, the five major non-governmental organizations issued a statement of intent to work together towards sustainability reporting standards, further motivating sustainability efforts (Eccles 2020).

With this backdrop, manufacturers are seeking ways to approach their own sustainability journeys. In 2019, 90% of companies in the S&P 500 (Standard and Poor's 500) (about half of which manufacture goods) published sustainability reports and discussed how to integrate their supply chains into sustainability efforts (Matthews 2019). SMM are now poised to embrace sustainability and need the support of technology and standards to do so. As background for subsequent discussions, this section outlines the business case for SMM to pursue sustainability efforts in terms of the key business drivers and direct financial materiality, and then identifies reported barriers for SMM in the pursuit of sustainability projects.

2.1 Sustainability and Manufacturing

From a business perspective, key areas that benefit from sustainable practices are brand, operational performance, employee engagement, industry cooperation, and investor relations. Each of these areas is described below.

(1) Brand: Trends in consumer purchasing have led to a shift in consumer behavior with a growing emphasis on sustainability. "Nearly two-thirds of consumers across six international markets believe they 'have a responsibility to purchase products that are good for the environment and society' — 82% of consumers in emerging markets and 42% in developed markets" (Whelan and Fink 2016).

(2) Operational Performance: The connection between sustainability practices and bottom-line performance is becoming clearer over time as more companies report their improvements. For example, "since 1994, Dow invested nearly $2 billion in improving resource efficiency and saved $9.8 billion from reduced energy and wastewater consumption in manufacturing. In 2013, GE reduced greenhouse gas emissions by 32% and water use by 45% compared to 2004 and 2006 baselines, respectively, resulting in $300 million in savings" (Whelan and Fink 2016).

Operational performance that exceeds environmental regulations and outperforms peers on those dimensions has also been demonstrated to earn higher market capitalizations (Murphy 2002).

(3) Employee engagement: Employee engagement, as well as future employees who are now students, are reported to be positively influenced by sustainability efforts. For example, "76 percent of Unilever's 170,000 employees feel their role at work enables them to contribute to delivering to the sustainability agenda, and about half of all new employees entering the company from university cite Unilever's ethical and sustainability policies as the primary reason for wanting to join. In a world where fewer than 20% of people go to work and feel happy, a workforce like Unilever's, where almost 80% of people feel engaged, is a competitive advantage" (Polman and Bhattacharya 2016). Employee engagement drives at why we work, and firms can transfer favorable business purposes to employee purposes. One study, focusing on over 5000 firms that had or had not adopted hyper-regulatory environmental standards, found that those that had enjoyed a significant premium in employee productivity over those that had not (Delmas and Pekovic 2013).

(4) Industry Cooperation: Through standards development efforts and industry coalitions, industry peers can band together to conform to sustainable practices that advance their industries. Michael Kobhari, VP of Sustainability for Levi Strauss & Co., stated that "The Sustainable Apparel Coalition brings brands and vendors together in an equal partnership to drive impact" (Apparel Coalition 2020). Global organizations such as Apple (Apple Newsroom 2020), Unilever (Prakash 2020), and Microsoft (B. Smith 2020) are beginning to use their scale to advance sustainability improvements in their supply chains, which is creating downward pressure to support sustainability integration for manufacturers that are key suppliers. We examine more evidence of these trickle-down motivations across a wide base of industries in Section 4. Additionally, organizations such as The Sustainability Consortium, which is spearheaded by large multinational organizations, have been formed "to help companies across the full spectrum of their business to create transparent supply chains and lead the industry forward" ("The Sustainability Consortium" 2020).

(5) Investor Relations: Through adherence and alignment with the investor community's preferred metrics and disclosure, industry members can have a clearer understanding of which key sustainability areas are the most important to their investors and deserve their attention. The motivations for sustainable investing have moved to private equity, where a 2019 PWC report discovered that over two thirds of private equity houses "use or are developing KPIs to measure ESG [Environmental, Social, and Governance—the three pillars of sustainability] performance" (Jackson-Moore et al. 2019).

2.2 Financial Materiality and Sustainable Manufacturing

Given these strong motivations, sustainable manufacturing seems worthy of pursuit for manufacturers, but the path towards this goal is poorly defined. One thing is clear: the financial implications of pursuing sustainability goals need to be clearly understood and addressed. Financial materiality — i.e., the relative significance of an issue to the financial condition of the company — can serve as a compass for manufacturers to identify which sustainability issues are most pertinent for their business.

As the availability of data and its quality have improved over time, investment research firms are able to identify the key issues that are the most financially material within an industry. Investment research firm Morningstar, Inc. describes their process for evaluating the risk posed to a company by ESG factors, beginning by assessing the firm's overall exposure to material ESG risks in both its operations and its products and services, followed by an evaluation of how the company's ESG risk is mitigated through specific actions taken (Hale 2019). By focusing on information that is material for financial decision-makers, practitioners can narrow the scope for targeting sustainability improvements to those that (1) have a direct impact on financial performance and (2) are important to investors and, in turn, society. Focusing a manufacturer's efforts this way creates a virtuous cycle in which the manufacturer can see near-term impacts of their changes on the business's bottom line, creating more goodwill for future efforts.

The investment community turns to a host of organizations, both for-profit and non-profit, whose missions are related to fostering improvement on relevant sustainability disclosure for public audiences. These organizations serve varying purposes, from setting standards and guidelines to evaluating company performance and providing sustainability scores to their respective audiences. Notable organizations include the Task Force for Climate-Related Financial Disclosure (TCFD)—formed out of the United Nation's Financial Stability Board—Climate Disclosure Standards Board (CDSB), Global Reporting Initiative (GRI), and the Sustainability Accounting Standards Board (SASB). Unlike its peer organizations, SASB standards are not designed to communicate with multiple stakeholder groups, but rather focus on one group: the investment community. The organization's mission is "to help businesses around the world identify, manage, and report on the sustainability topics that matter most to their investors" ("Sustainability Accounting Standards Board" 2018).

With this scope, SASB can add value to both investors and industry users by addressing issues that demonstrate financial value. In essence, SASB metrics are designed to highlight profitable sustainability. Recently, the demand for investments that are managed in a more sustainable manner has skyrocketed. According to CNBC, "Whether it's in equities, government bonds, ETFs (exchange-traded funds) or hedge funds, investors around the world are demanding socially and environmentally conscious options" (E. Smith 2020). This demand has generated a wave of investments into the ESG category. In 2019 investors allocated \$20.6 billion (USD) in new funds to this investment style (Iacurci 2020). As of 2019, global firms, which collectively hold over \$48 trillion in assets under management ("Sustainability Accounting Standards Board" 2018), support SASB disclosure standards. This report focuses in on SASB standards due to their widespread support among industry leaders, positive financial implications for practicing manufacturers, and recent emphasis on engaging the manufacturing supply chains—i.e. the SMM community—in reporting.

2.3 SASB's Imprint on Manufacturing

Starting in 2012, SASB formed a working group with members of both the investor and industry communities to begin formulating a cohesive body of standards. SASB released its standards after six years of work in November 2018. The SASB sustainability topics fall under five broad dimensions: Environment, Social Capital, Human Capital, Business Model and Innovation, and Leadership and Governance ("SASB Materiality Map" 2018). SASB's multi-year process of

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metric definition constituted significant market input and research and has since been studied and proven to correlate with improved share price, as well as improved margins for certain industries (Beal et al. 2017; Khan, Serafeim, and Yoon 2016). As of the end of 2019, 349 multinational corporations had published corporate sustainability reports referencing SASB metrics and over 100 are currently reporting the metrics ("Letter to US Securities and Exchange Commission" 2019).

SASB's standards are tailored to fit each specific industry for which they set standards. SASB's framework outlines 11 sectors, each with several industrial sub-sectors to classify companies. In total, SASB has built 77 sets of industry standards across each of the different subsectors. Figure 3 illustrates the level of specificity that SASB brings across the different sub-sectors. The figure draws from the dimensions of SASB reporting that are most relevant to manufacturing operations—*Environment* and *Business Model and Innovation* ("SASB Materiality Map" 2018). The sizes of the boxes indicate the relative importance of standards pertinent to operations within the sectors. The figure shows that operations-focused metrics occur across all 11 sectors.

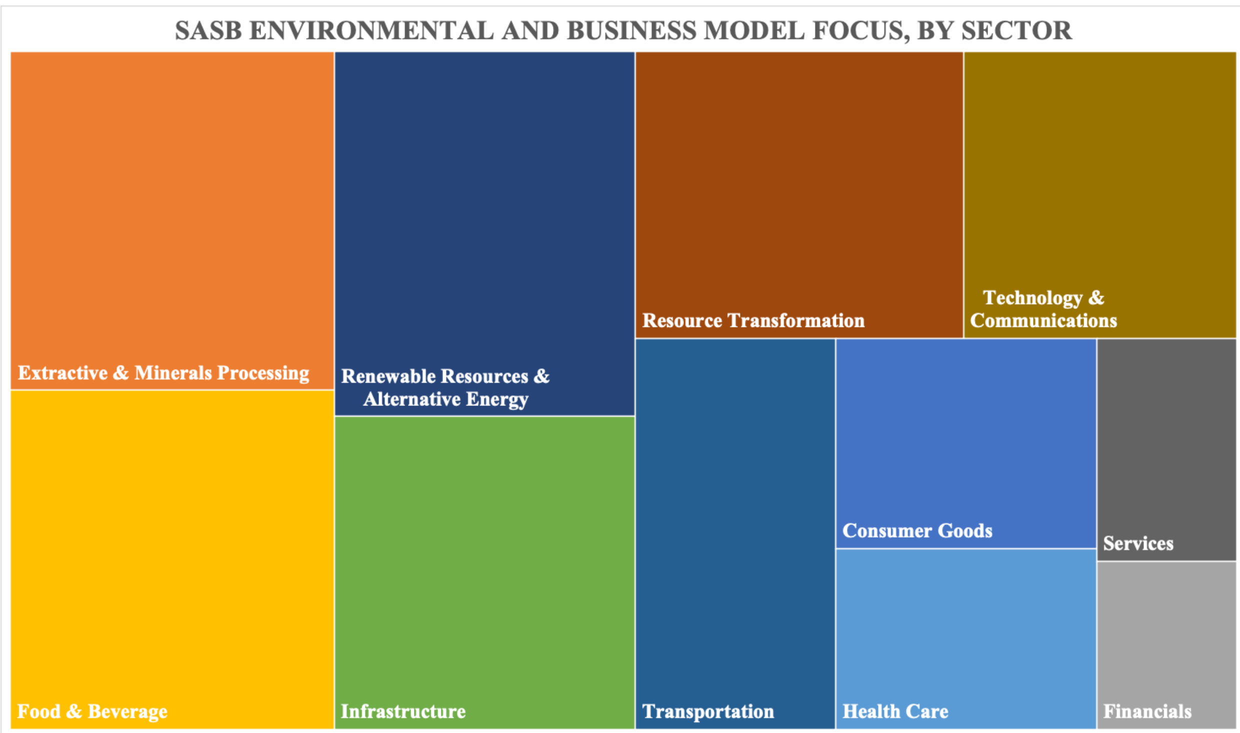

Figure 3: Distribution of operations focused standards across SASB Categories

A review of the standards shows the connection between SASB and manufacturing. The scope was narrowed to the nine sectors with the most sizeable manufacturing presence—*Health Care*, *Extractive and Minerals Processing*, *Infrastructure*, *Technology and Communications*, *Resource Transformation*, *Food and Beverage*, *Consumer Goods*, *Transportation and Renewable Resources*, and *Alternative Energy*—and 38 manufacturing-centric industries within those sectors were analyzed for operational initiatives that led to sustainability improvements. Figure 4 shows the prevalence of initiatives that pertain to sustainability in the areas of

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- Supply Chain Management (SCM),
- Waste Management,
- Air & Greenhouse Gas (GHG) Emissions,
- Employee Health & Safety,
- Product Lifecycle Methods,
- Energy Management, and
- Water Management.

Product Lifecycle Method initiatives differ in granularity and externality, and include specific practices such as product life cycle management, life cycle analysis, and life cycle inventory (Haapala et al. 2013; Marra et al. 2018; Trotta 2010). All of these methods address impacts across the full life cycle of a product from design, through the use phase, to the end of life.

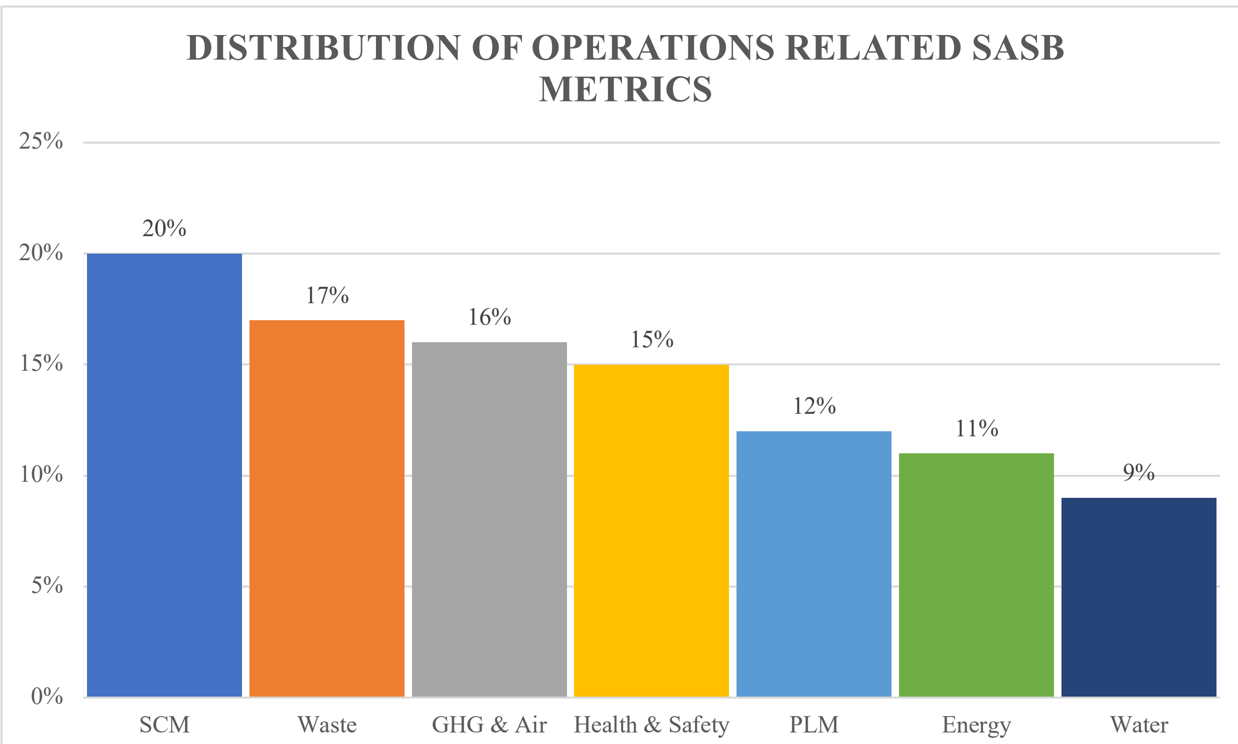

Figure 4: Distribution of SASB Metric Categories Pertaining to Operations

Note that risk management is a motivation to pursue sustainability efforts within each of the listed categories. Firms with mature risk management strategies have been shown to outperform competitors financially, largely driving an industry-wide movement towards centralized enterprise risk management (ERM) programs (Anderson 2019). The type of data required by ERM can extend into the supply chain, which leads to frequent guidance on supply chain conformance as a component of sustainability (Institution for Responsible Business Conduct 2020; World Resources Institute and World Business Council for Sustainable Development 2004). For SMM, this translates to market access (ASME Open Research Forum 2013). We examine evidence of market access as an outcome of sustainability for SMM.

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2.4 The Reported Barriers to Sustainability

In light of these motivations for pursuing sustainability, we looked for evidence of what prevents SMM from taking on these projects. To understand the barriers to sustainable manufacturing we relied on consensus reports from the American Society of Mechanical Engineers (ASME) and Indiana University from 2013 that identified sets of barriers that discourage SMM from pursuing sustainable manufacturing (ASME Open Research Forum 2013; Carley et al. 2014). Reflecting on the common themes in these reports, we hypothesized the following set of barriers to sustainability:

- **Strategic alignment**: sustainability initiatives are perceived to be at odds with growth strategies in terms of providing what customers demand or what the business needs to acquire those customers.
- **Financial outlook**: the stigma of concessionary performance is common in the context of sustainability investments, which is often amplified by inadequate decision rules such as payback period or when stakeholders familiar with the environmental opportunity costs (such as utilities managers) are not involved.
- **Organizational feasibility**: a lack of organizational structure, workforce readiness, or technical capabilities to progress towards sustainability goals.

Strategic alignment reflects how firms can generate benefits across the entire organization and create value for their customers. For example, cost reductions in employee retention and heightened engagement might be derived from operations processes that explicitly track and reward improved environmental and social performance. A perception that sustainability projects result in poor financial performance carries from the traditional perspective that management will have to go out of their way or pay a premium for sustainability results for a given type of project. Other biases can manifest from investment and budgeting processes that fail to consider the full scope of cost and revenue potential of investments, which can be captured with decision rules that account for opportunity costs. Finally, barriers of organizational feasibility stem from the belief that the proposed initiative would require too much unproven capacity from the workforce, either to support management systems or the technologies necessary to follow through on initial investments and mitigate back-sliding.

3. Methodology

The goals for this study are to address the reported barriers that prevent SMM from pursuing sustainable manufacturing initiatives, refine them, and identify means to overcome the barriers. We reviewed several different data sources to understand and address this challenge. To refocus the problem statement, we partnered with public/private programs under the U.S. Departments of Commerce and Energy to directly test our secondary research. Finally, we delved deeper into data from the same institutions as well as corporate sustainability reports from leading manufacturers aligned to SASB standards to assess the historical outcomes of SMM investing in sustainability.

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3.1 Primary research towards refocusing the barriers

First, we conducted primary research to refocus the barriers that this group of manufacturers faces in embracing sustainability as an objective. This included the following:

- Discussions with subject matter experts including three roundtables with leaders from Department of Commerce Manufacturing Extension Partnership (MEP) ("MEP National Network Success Stories" 2019) and the Department of Energy's Industrial Assessment Centers (IAC) ("Industrial Assessment Centers" 2020).
- An analysis of the database of projects driven by the IAC program. The IAC program works directly with small manufacturers to identify opportunities for energy savings. The program maintains publicly available, forward-looking project data collected over decades of operation (IAC University 2020).

A degree of overlap across the institutions was present in the roundtable participation, allowing us to observe the effect that interacting with different stakeholders has on initiative acceptance. For example, while MEP centers were found to interact with upper management through their missions of business development, the Department of Energy's IAC engagements more often involved the manufacturing operations-focused stakeholders and looked more narrowly at energy improvements. The following questions were used during the roundtables to understand the state of the practice for pursuing sustainable manufacturing, the value that SMMs currently look for in implementing sustainable manufacturing practices, and the role that standards play in SMM operations in the context of sustainability goals.

State of the practice:

- With the benefits outlined (Brand Equity, Operational Improvement, Employee Engagement, Coalition Membership, Exit Valuation) in mind, which are the top issues referenced in sustainability requests from manufacturers?
- How often are projects funded that come under the scope of:
  - Risk Management
  - Cost Savings
  - Market Access
  - Environmental Impact Reductions
- What other motivators for sustainability have you experienced?

Value of sustainability:

- Are sustainability projects typically asked for by manufacturers or suggested by MEP or IAC? Please add context if helpful.
- How are the sustainability forces highlighted (Supply Chain Conformance, Air Emissions & GHG, Health & Safety, Waste, Water, Energy) typically factored into the ROI or payback period for your clients?
- Do the sustainability forces highlighted ever amount to a competitive advantage for clients? If so, how?

- Is there a difference in cost/implementation barriers in companies that have implemented sustainability initiatives before?
- What is the relationship you see between expanded market access and supply chain conformance?

Role of standards in achieving sustainability goals:

- Which standards do you use?
- What would make standards more helpful?
- What is different about projects grounded in standards?
- What do you find helps drive replication of sustainability initiatives across sites and what makes these initiatives best suited to innovate on?
- Do you observe a greater appetite for standards-based work in companies that have experience with using them?
- Have standards been helpful in organizational (e.g., maintenance, engineering, operations) alignment? If so, how?

Finally, we corroborated these findings with a review of the quantitative IAC data. IAC's work with manufacturers to recommend specific improvements to reduce environmental impact and improve business results. These recommendations are based on a review of the facility and a return on investment (ROI) analysis for each recommendation. The DOE has tracked the implementation of those recommendations since 1987, including those recommendations that were rejected by the manufacturers. The data, spanning from 1987 to 2020, shows that of the 138,745 recommendations made by IAC, slightly over half (51.49%) were recorded as *Not Implemented* resulting in more than 71,000 rejected recommendations. The IAC collected over 49,000 data points on the cause for these rejections. We aggregated those rejections to gain more context on the barriers to sustainability.

3.2 Baseline method of evaluating outcomes

Our experiments were designed to generate a common understanding of expected outcomes based on existing practices affected by the three chief reported barriers: strategic alignment, financial outlook, and organizational feasibility.

Corporate sustainability reports that elected to report SASB data were selected from three SASB-defined sectors where the reports were readily available from the SASB website and the manufacturing component was significant: *Resource Transformation*, *Health Care*, and *Transportation*. To focus on manufacturing, the industries examined from these sectors include biotechnology, pharmaceuticals, medical equipment and supplies, aerospace and defense, containers and packaging, electrical and electronic equipment, industrial machinery and goods, chemicals, automobiles, auto parts, marine transportation, and rail transportation. Forty-five companies on the SASB website listed sustainability reports under this grouping of industries ("SASB Reporters" 2018).

To extract the most value from corporate sustainability reports, we leaned on recent research from Wanner and Janiesch (Wanner and Janiesch 2019), who evaluated the credibility and pattern of content found within these reports. While the usefulness of sustainability reports has improved over the last twenty years, gaps in completeness and accuracy remain. From the perspective of investors, useful information within sustainability reports has been linked to the ISO 14000 and 9000 families of standards (Lyndenberg and Wood 2010). The use of standards makes the reports more reliable. We identify sustainability-related ISO standards used at the largest global manufacturers to reveal the strategic implications around sustainable investments in industry.

To further examine whether supply chain conformance creates an immediate incentive to adopt certain ISO or sustainability-related standards, we examined drivers for sustainable ISO standards adoption directly through MEP data by categorizing retrospective results and comparing frequency distributions. We examined project data from 2016 to 2020 and examined over 27,000 surveys for their reported benefits. We used this data to understand strategic motivations for purely sustainable or standards-driven initiatives in SMM.

The expectation of financial concession in environmentally sustainable investments for SMM was evaluated through an analysis of IAC data, where forward-looking cost savings for sustainable manufacturing investments are tracked alongside investment and firm data. Going back two years, all forecasted cost savings as a result of reduced utility expenditures were calculated with regional data at the time of the recommendation by the IAC. To address the notion of feasibility, we compared the size of cost savings relative to investment size and revenue size to reveal the financial characteristics of environmentally sustainable investments and the presence of "low hanging fruit" where firms in the smallest band of revenues still find profitable investments.

4. Results

Our analyses were conducted in the sequence presented in this section, building on findings to thoroughly respond to a refocused problem statement. First, we corroborated the most reported barriers to sustainability through portions of our IAC and MEP roundtable discussions and IAC database analysis. We found strong evidence that the common perception of strategic alignment, financial outlook, and organizational feasibility were barriers to sustainability among industry practitioners and consultants.

Then we examined these barriers more directly through corporate sustainability reports and public/private partnership data, including the MEP and IAC databases. These analyses revealed the value of sustainability investments, as well as the value of particular standards related to sustainability issues. The value of these initiatives was observed in SMM through either retained revenues and jobs or reduced costs. Outcomes depended on whether manufacturers focused on those standards or more narrowly scoped investments, respectively.

4.1 Confirming the reported barriers towards sustainability

We framed our work to respond to the reported barriers to sustainability. Consensus reports demonstrated that strategic alignment, financial outlook, and organizational feasibility characterized the common barriers (ASME Open Research Forum 2013; Carley et al. 2014). To validate that these were the proper barriers for testing, we held a series of roundtables with MEP and IAC experts. Finally, we examined the IAC database rejection codes. This research largely corroborated what was discovered in the literature and provided depth to the barriers.

4.1.1 MEP and IAC Roundtables

In the series of roundtable discussions with SMM experts from MEP and IAC, we explored the implications and nuances of the barriers to sustainability for SMM.

SMM were observed to commonly prioritize operational improvements tied to immediate cost savings or otherwise react to supply chain pressures. Sustainability initiatives were not often perceived to survive the threshold for immediate cost savings. Interestingly though, they tended to relax payback period constraints after subsequent sustainability projects. The ubiquitous use of payback period and not lack therein of considering opportunity costs across the organization was another significant barrier to sustainability efforts, according to the roundtables. We learned that when the involvement of upper leadership and finance departments was secured, these barriers were often mitigated.

As for strategic motivations towards sustainability, voluntary sustainability standards were most likely to be passed down when a manufacturer had foreign ownership. Similarly, maintaining large multinationals as clients was another common motivator for sustainability projects as was the use of standards in their deployment. Succession of ownership to younger generations was observed as coinciding with explicit demand for sustainable investments. Otherwise, the motivation for standards deployment efforts was limited since the return on investment (ROI) for standards certification can be difficult to project.

The extent to which standards were deployed to meet sustainability goals also varied. The use of standards helps achieve reliable and repeatable results and is foundational to reporting metrics. Within ISO, three standards families were identified as being broadly used and supportive of sustainability efforts: ISO 14000: Environmental Management, ISO 9000: Quality Management, and ISO 50000: Energy Management. While ISO 14001 is useful as a framework for estimating environmental performance for manufacturers of all sizes, ISO 50001 certification was often mentioned as being more appropriate for large manufacturers. Still, ISO 50001 can inspire energy cost savings for projects of any size, as was shown by the success of the US Department of Energy's 50001 Ready Program (US Department of Energy 2021). The chief standards-based gap observed was for guidance on the measurement of environmental sustainability data. That is to say that once goals have been set and organizational alignment attained, the open question of how exactly to measure sustainability performance remains.

4.1.2 IAC Project Rejection Data

The IAC's data allows manufacturers to code their rejected projects with one of 18 causes. Through examination, we grouped the causes into five encompassing tranches: *Financial*, *Feasibility*, *Buy-In and Risk Tolerance*, *Workforce and Expertise*, and *Other* (Figure 5). We found that *Financial* motivations mapped onto our financial outlook barrier, *Feasibility* and

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Workforce and Expertise tracked with our organizational feasibility barrier, and *Buy-in & Risk Tolerance* matched with our strategic alignment barrier.

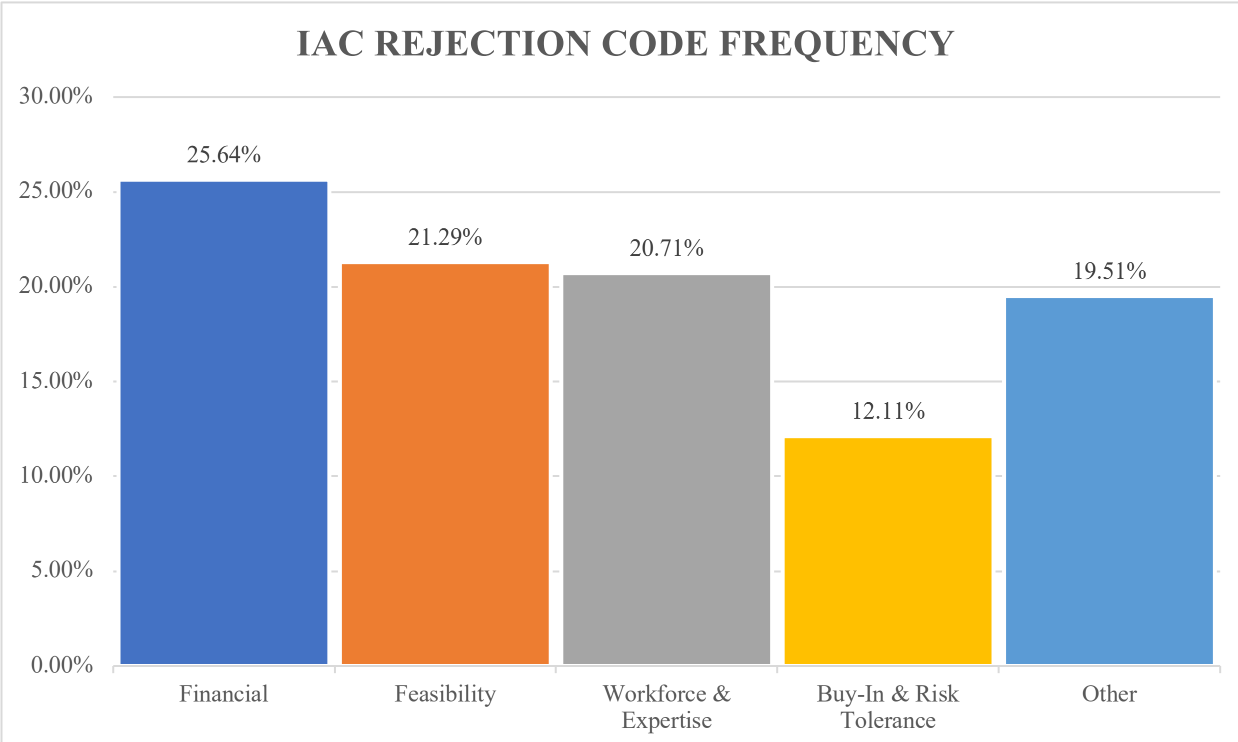

Figure 5: Distribution of IAC rejection codes

The shopfloor level of detail available in IAC data does not give us sufficient scope for discerning the role of corporate strategy in rejecting environmentally sustainable investments. However, we can observe financial and feasible motivations. Financial justifications were straightforward, based on determined challenges in cash flows and initial outlay. The feasibility aspect was more nuanced; however, we believe that the underlying responses that make up *Workforce & Expertise* and *Feasibility* are similar. For example, several aspects of *Feasibility* are components of the status quo, as reflected in categories such as *Unacceptable Operating Changes*, or *Schedule Conflicts*. *Workforce & Expertise* are directly people challenges, such as lack of the necessary workforce to implement, bureaucratic restrictions, or general lack of expertise.

In summary, the barriers reported in the open literature were confirmed through both expert interviews and historical data. In exploring the nuance of these barriers, we found salient and addressable aspects for each. The barrier of *strategic alignment* can be in part attributed to limited emphasis on sustainability goals within the corporate strategy. The lack of corporate focus can prevent the sustainability objectives from effectively integrating into operations. The *organizational feasibility* barrier is perpetuated by a lack of strong guidance on how to approach sustainability efforts at the operational level. Standards and education can be brought to bear to address this barrier. The barrier of *financial outlook* is hamstrung by a lack of appreciation for both financial and other opportunities that sustainability efforts offer.

4.2 Evaluating the barriers towards sustainability

With this robust understanding of the reported barriers, we then formulated our tests. We started with corporate sustainability reports based on SASB to examine the strategic implications of global manufacturing sustainability leadership to SMM. In these reports, standards were commonly cited as foundational to sustainability progress, namely the ISO 9001, 50001, and 14000 series as discussed below. Then, we examined the MEP database to analyze the results of pursuing these standards. Finally, we used the IAC database to directly inform a baseline for environmentally sustainable investments made by manufacturers across a range of investment sizes, revenues, and industries. Our analysis of historical data from MEP, IAC, and corporate sustainability highlighted three findings relevant to the identified barriers:

1. Multinational manufacturers make consistent use of particular ISO standards to structure and signal sustainability investments and progress, and this strategy is being increasingly expected of suppliers.
2. ISO certifications for SMM are most likely to result in retained sales and jobs than any other category of recorded factors, supporting the notion that supply chain conformance is a value proposition for standards related to sustainability.
3. A significant share of environmental improvement projects demonstrates large cost savings while requiring minimal investments, even for manufacturers with small revenues.

These findings challenge underlying assumptions on which the barriers are based and more motivate SMM to refocus their decision making.

4.2.1 Environmental and Quality Management Standards Characterize Sustainability for Multinational Corporations

To understand which approaches to improve sustainability were successful among leading manufacturers, we analyzed industry reports electing to incorporate SASB standards. These reports highlighted that sustainability efforts are driven by standards as well as new technologies that improve the capability and communicability of sustainability metrics. Within the corporate sustainability reports we examined ISO standards as tools for organizations to set, track, and achieve sustainability targets. Focusing on industrial organizations that have committed to reporting SASB metrics, we noted the frequency of standards referenced and their context.

Three standards efforts stood out as being particularly impactful. Of the 45 sustainability reports reviewed, 89% referred to the ISO 14000 family of standards on environmental management in the context of their own systems and life cycle assessment initiatives. The next most common were the ISO 9001 quality management and ISO 50001 energy management standard certifications, at 42% and 19%, respectively. Supply chain content of the reports ranged from brief discussions of the values in their procurement processes, to the active inquiry of environmental data from their suppliers—referred to as Scope 3 reporting[1]—to screening for ISO certification. The most recent revision to the ISO 14000 family of standards directly incorporates Scope 3 data reporting. Standards were mentioned most frequently in sections of the reports that addressed environmental management, then supply chain management, and finally risk management.

In the most robust discussions around the ISO 14000 series, lifecycle management (LCM) and life cycle assessments (LCA) emerged as the most common sustainability practices. These drove environmental sustainability topics ranging from energy, waste, water, GHG, to air emissions. Our review of these reports indicated that where SMM seeking contracts are concerned, the material covered in the ISO 14001 and 9001 standards could serve as a reasonable proxy for the expectations of industry leaders. The ISO 14000 and 9000 families of standards are helpful for acquiring and maintaining contracts with the largest multinational firms, making standardized approaches to sustainability a notable growth strategy. In general, large multinationals pressured by stakeholders to report Scope 3 data are applying pressure to suppliers for environmental and social reporting data.

4.2.2 Standards Focus Results on Retained Sales and Retained Jobs

To understand the linkages between sustainability and standards within corporate sustainability reports, we look to MEP data to baseline expected results. MEP data is based on retrospective interviews with manufacturers, usually about six months after project completion. Therefore, these reports highlight short-term results, which allow us to directly examine some of the perceptions around sacrificing short-term results for sustainability. MEP centers frequently engage with corporate-level personnel, mainly because their consultations evaluate manufacturers' greater business outlook and are not focused exclusively on operational improvements. This broad lens captures a larger scope of work than what could be learned from IAC data and includes ISO certification and training. Analyzing project survey data from 2016 through to 2020, over 27,000 projects were examined for significant trends in outcomes. Projects were categorized into three types by MEP: (1) *ISO-Based Sustainability*, (2) *Non-ISO-Based Sustainability* , or (3) *Other*. We focused on the ISO-based projects identified in the corporate sustainability reports of multinationals working with SASB, namely ISO 14000 environmental and ISO 9001 quality management standards, as well as the other sustainability-related projects. Outcomes were determined from survey results approximately six months after project completion to assess observable results. The results examined within this dataset do not account for expected future results. Outcomes were categorized as *Increased Sales*, *Retained Sales*, *Increased Jobs*, *Retain Jobs*, and *Cost Savings*. Approximately 24,000 projects were coded as *Other*; 2,300 projects as *ISO-based Sustainability*; and 900 projects as *Non-ISO-Based Sustainability*. To marshal sample size-related issues, a cross validation approach was applied to

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[1] According to the EPA, Scope 1 emissions are defined as the greenhouse gas emissions attributable to sources owned or controlled by the entity. Scopes 2 and 3 describe greenhouse gas emissions attributable to the production of energy consumed by the entity and independent entities impacted value chain activities, respectively.

the chi-squares test to set equivalent sample sizes of n=75 and average test results across 25 iterations.

Statistically significant differences at the 90% confidence level were found between mean outcomes for *ISO-Based Sustainability* projects and *Non-ISO-Based Sustainability* projects. (Figure 6) *Retained Sales* and *Retained Jobs* were reported as short-term outcomes for approximately 51% of *ISO-Based Sustainability* projects. *Non-ISO-Based Sustainability* projects posted observed frequencies of 21% and 29%, respectively. Additionally, statistical significance in the difference of means was detected between *Non-ISO-Based Sustainability* projects and *ISO-Based Sustainability* projects. *Non-ISO-Based Sustainability* projects were found to result in immediate *Cost Savings* 54% of the time, while *ISO-Based Sustainability* projects only resulted in immediate *Cost Savings* 37% of the time.

While projects encoded as *Other* did not differ from any other category at a statistically significant level, expected results fell between the extremes for almost every outcome. *Retained Sales* and *Retained Jobs* demonstrated strong to medium correlation at the 99% confidence level for every project category. That is to say that where *Retained Sales* could be expected (such as at the 51% rate for *ISO-Based Sustainability* projects), *Retained Jobs* were highly likely to follow.

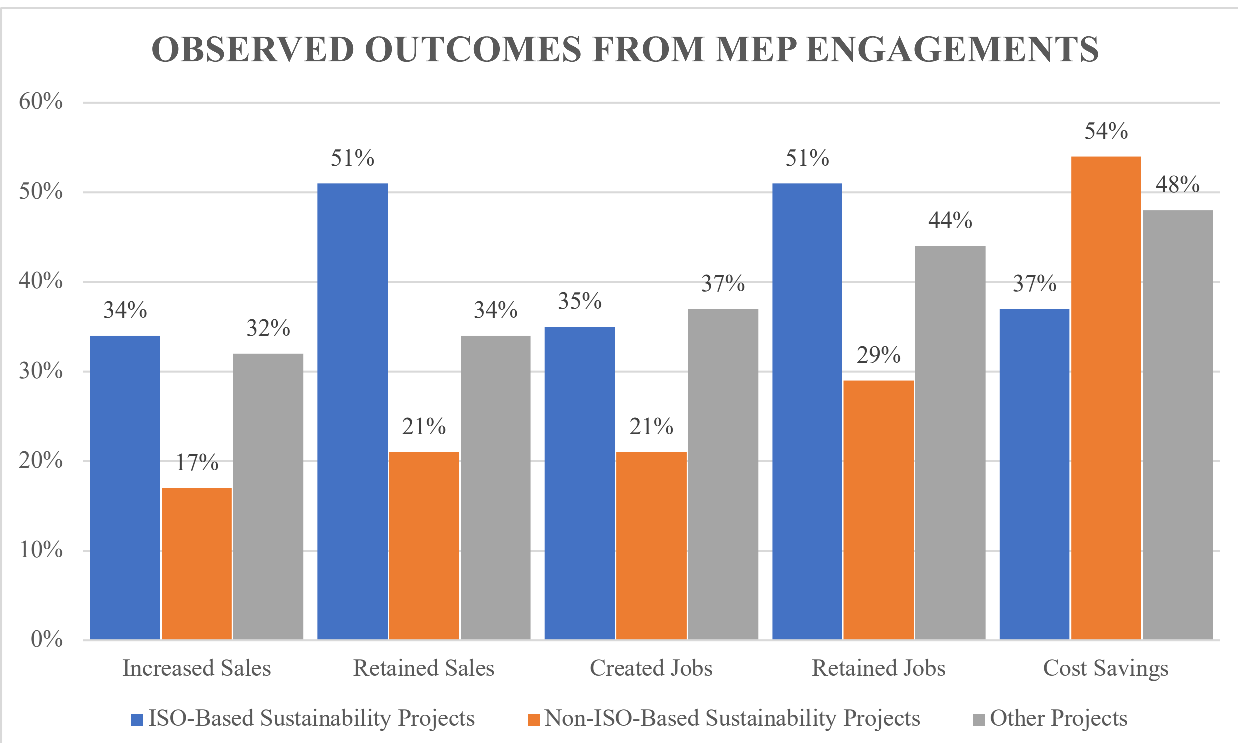

Figure 6: Frequencies for observed project results by project classification. Bars with comparative labels highlight statistically significant relationships.

The strong consistency of *Retained Sales* and *Retained Jobs* for exclusively *ISO-Based Sustainability* projects gives us reason to further consider the role of supply chain conformance in the adoption of standards for SMM. In addition to confirming the prevalence of these same standards in corporate sustainability reports for industry-leading multinational corporations, we observed this narrative during the MEP roundtables where it was reported that large clients sought ISO certification from their suppliers. We found the outsized frequency of grounding sustainability investments in specific ISO standards for revenue security or foregoing those ISO standards for cost savings notable as well. By building the organizational capability to invest in either modality, businesses might be able to quickly adapt to shifting market conditions.

4.2.3 Sustainability Improvements Save on Costs

While MEP data confirmed that sustainability projects demonstrated strong potential for immediate cost savings, IAC data gave us the ability to peer into the forward-looking expectations for firms that had made such investments. Of the implemented projects studied, 97% were principally energy, water, waste, or hazardous waste reduction cost savings, mirroring the SASB manufacturing topics. From 2019 to 2020, automated packing and in-house material generation projects generated the largest cost savings while achieving paybacks in close to one year. Optimized downtime and changing utility rate schedules presented the most rapid payback periods. Manufacturers ranged from plastics to aircraft parts and pharmaceuticals producers. Using data from the IAC program we tested two key hypotheses: (1) that “low-hanging fruit” projects exist as favorable investments, and (2) that these types of projects were available to firms regardless of size.

The IAC database provides estimated cost savings and real implementation costs along with firm size as measured by revenue. The most common IAC recommendations included high efficiency ballasts and compressed air management systems. Our approach does not account for the opportunity cost of competing budget allocations. By fully considering the implications of competing investments over a time-horizon that management believes it can accurately forecast, a clearer picture of investment options can form. Focusing on the cost savings alone, we divided the 150 manufacturer results into five equally populated bands by revenue and by investment size to test for significance in mean results. We did not find statistically significant differences in results for manufacturers across revenue or total investment quintiles.

In summary, we found the following:

- Firms of all revenues find valuable investments in sustainability at every price point (Figure 7).
- Even the smallest manufacturers can be expected to generate tens of thousands of dollars in annualized cost savings through the recommendations of the average IAC engagement (Figure 8).
- Larger investment sizes do tend to produce larger annualized cost savings; this is not a statistically significant relationship and thus even the smallest investments can produce cost savings similar to the largest investments (Figure 9).

The notion of financial outlook as a significant barrier to sustainability seems to warrant a more nuanced and intensive review after examining IAC data. Possible hypotheses to guide further testing might include linking the use of payback period as a decision rule to inconsistent evaluations of sustainability as financially beneficial. Separately, if the size of the firm is a proxy

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for the capacity to resolve organizational feasibility barriers, then the lack of statistical significance in cost savings and investment size between the smallest and largest manufacturers challenges organizational feasibility as a barrier since even the smallest manufacturers had significant cost savings.

These findings provide motivation for a closer examination of how change can be accelerate by small and medium manufacturers, the major class of manufacturers in the U.S. These manufacturers are also the least resilient to changes in their financial performance and thus are also the least prepared to initiate such changes without business incentives.

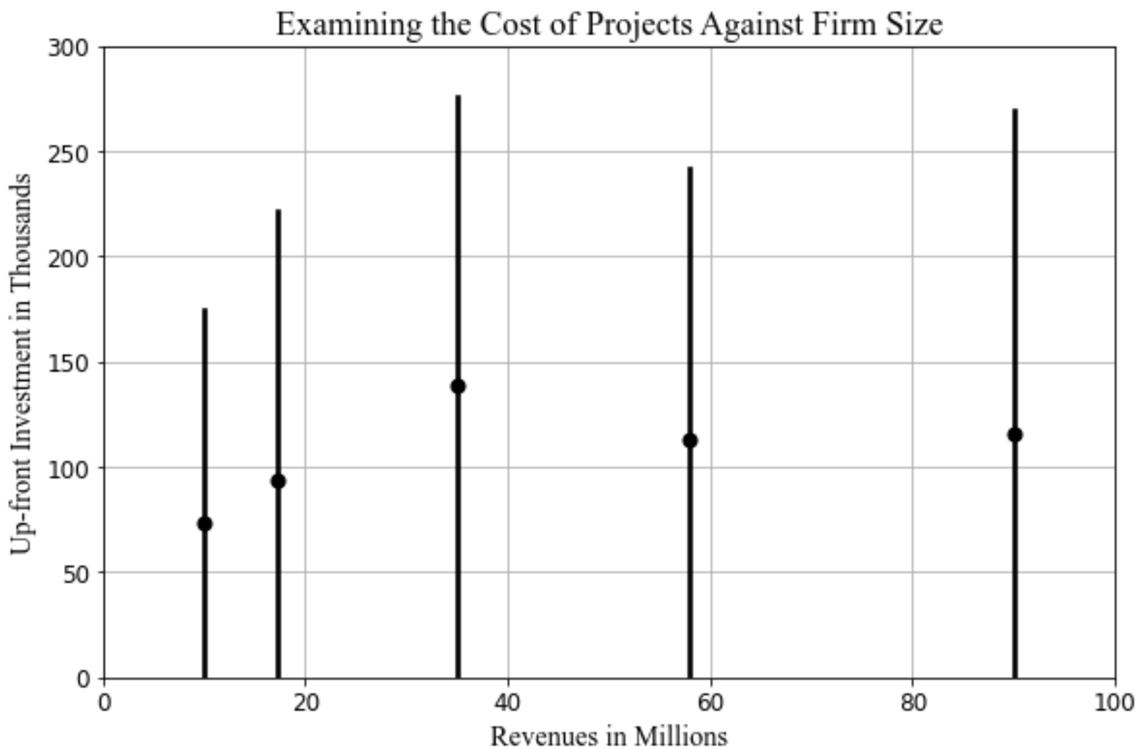

Figure 7: Trends in invesment size plotted against manufacturer revenue visualized by quintile means and quintile standard errors about their respective means.

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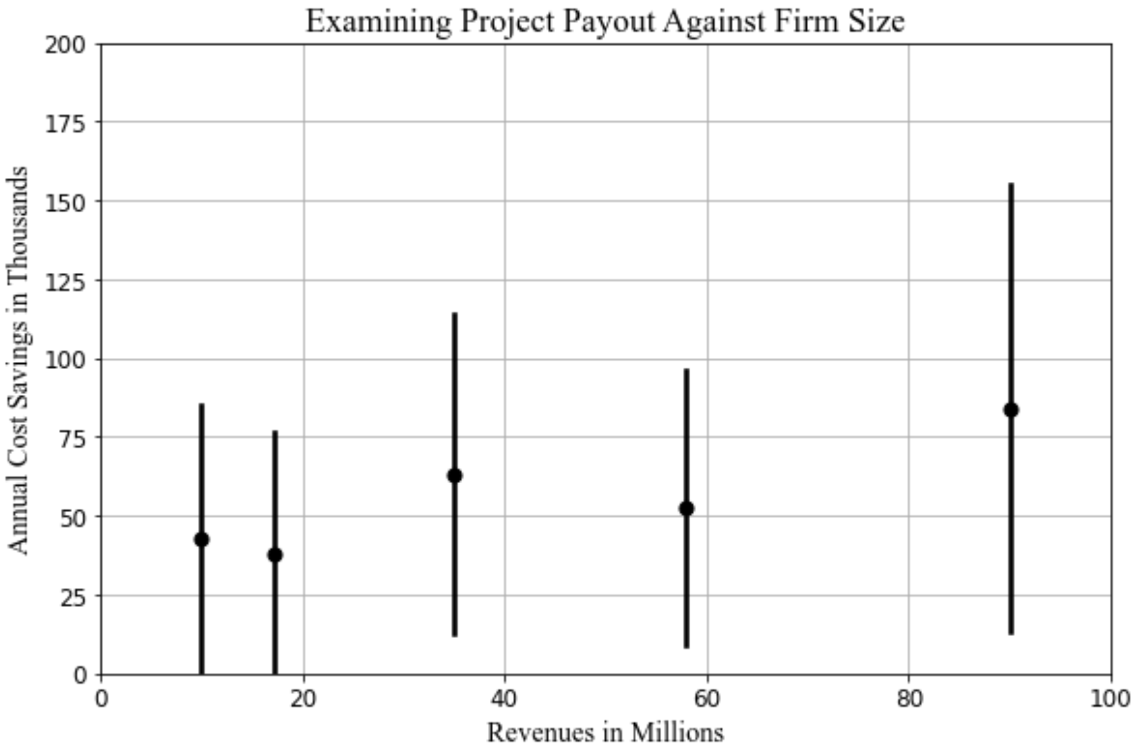

Figure 8: Trends in annualized cost savings against manufacturer revenues visualized by quintile means and quintile standard errors about their respective means.

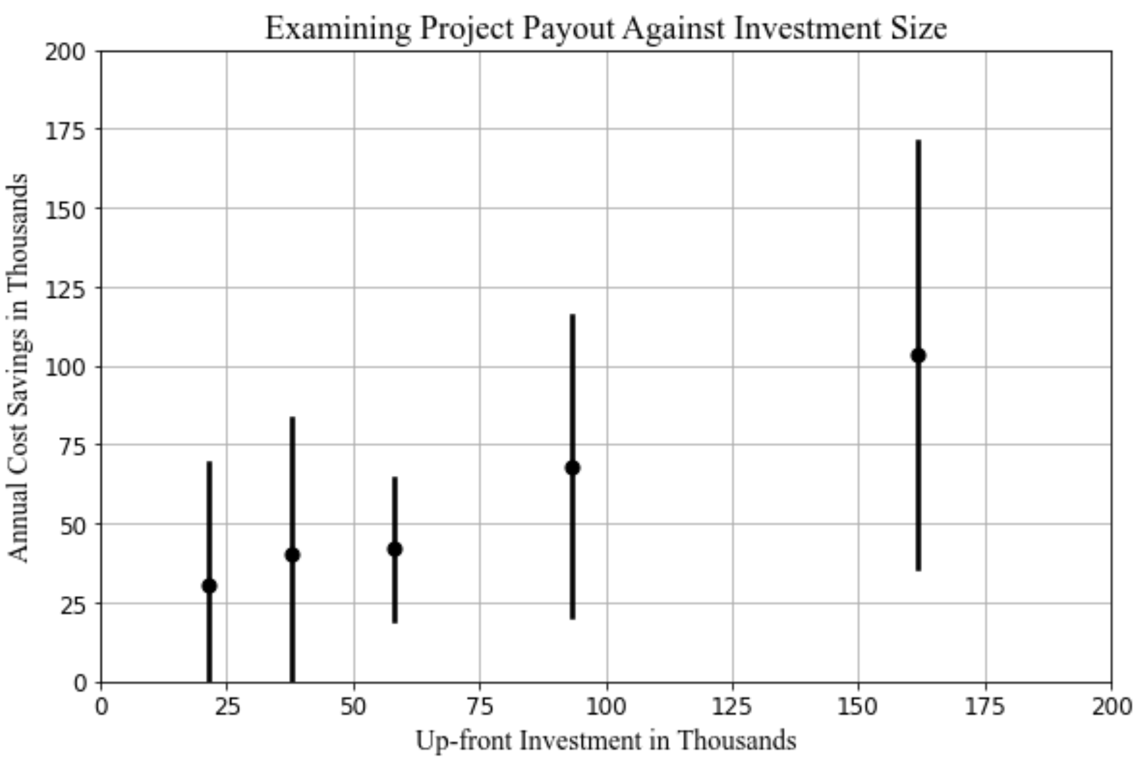

Figure 9: Trends in cost savings against investment size visualized with quintile means and quintile standard errors about their respective means.

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5. Discussion

Results of these analyses indicate that the underlying assumptions associated with the barriers to sustainable investments should be revisited. Sustainability investments seem to offer a range of strategic advantages and financial opportunities, even for the smallest manufacturers. The notions that ISO standards flagged by multinational corporations in their sustainability reports are important to their SMM partners and that sustainability alone drives significant cost saving opportunity were reinforced throughout our results.

From an operational perspective, standards exist that help guide the deployment of such initiatives. While overhead costs are associated with using the existing standards, integrating the standards into operating procedures opens opportunities and increases the potential for more sustainable manufacturing. The role of standards in guiding sustainability initiatives was commonly observed throughout corporate sustainability reports which contained SASB metrics. Existing ISO management standards for environmental management (14000 series), energy management (50001), and quality management (9000 series) are being leveraged by large corporations today to report on and achieve sustainability improvements. The standards tend to be used differently and more fully depending on the size of the manufacturing firm, as shown in Figure 10.

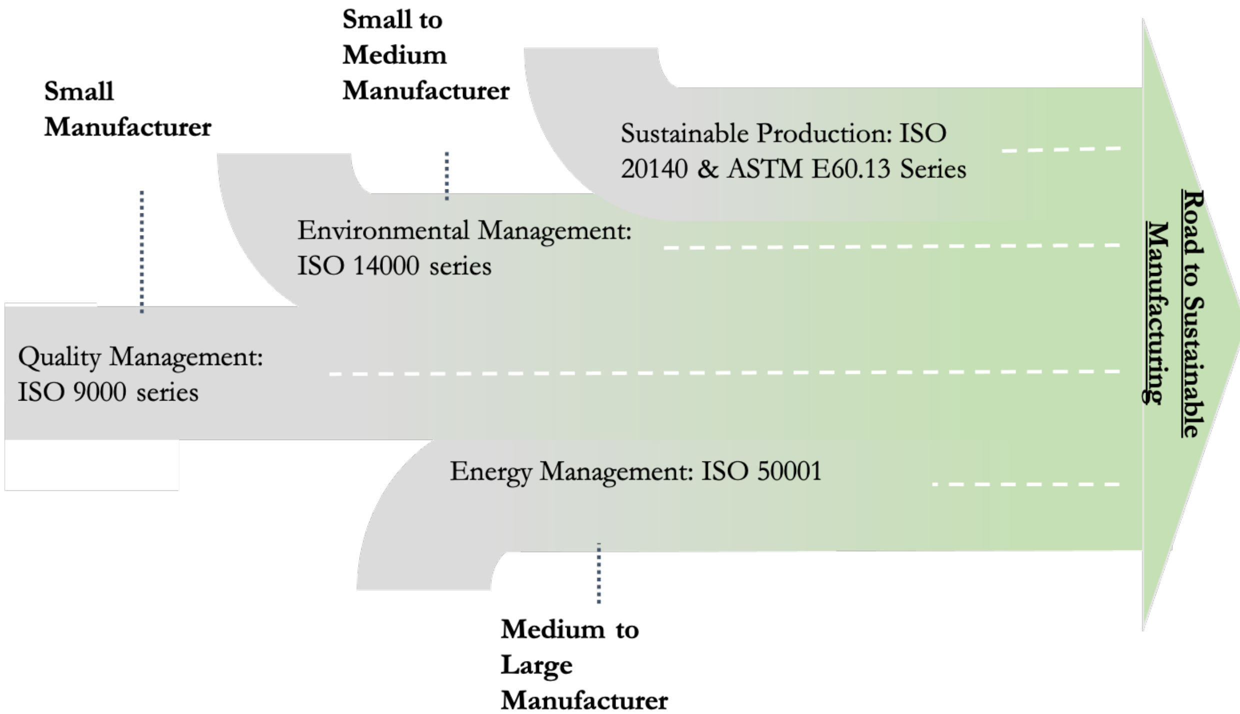

Figure 10: Sustainability standards roadmap, developed with input from roundtables.

The ISO 9001 and 14001 standards were commonly observed throughout corporate sustainability reports and MEP data. Additional standards are needed to provide guidance across all areas where sustainability impacts are an issue, e.g., material and waste reuse or water management.

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Addressing the strategic alignment barrier will help SMM move towards implementing sustainable solutions. Strategic alignment relates primarily to an enterprise's ability to recognize new principles of sustainability. The recognition must start at the organizational level with a commitment to sustainability efforts and be pushed through the organization to encourage innovation and initiative towards these goals. Standards will give practitioners the tools to address problems as they are found and provide a platform for innovating and measuring performance improvements.

Engaging the workforce is especially critical and will require decentralizing control of the solution space through continuous improvement practices. Continuous improvement principles are built on the concept of shopfloor innovation, which can also spur engagement from employees to close sustainability gaps (Bai, Satir, and Sarkis 2019; Carley et al. 2014). Decentralization allows for innovative sustainability measures to be taken at the point of impact, but this poses a challenge to accounting methods that try and reflect those measures. The Greenhouse Gas Protocol, one of the most cited guidelines on accounting and reporting environmental data within the SASB standards, also discusses the complexity that decentralization can bring to an effort, such as effectively measuring and reporting environmental data (World Resources Institute and World Business Council for Sustainable Development 2004).

The ISO 14000 series is a standardized approach to environmental management that enables an estimate of environmental impact; this standard has given way to a body of initiatives shifting the emphasis from management estimation to production level measurement (Sinha 2010). Emerging *smart manufacturing* technologies are evolving to improve manufacturing efficiency and allow for detailed measurements of resource use and waste production (Lu, Morris, and Frechette 2016). Our review of sustainability reports highlights a surge in innovative approaches to manufacturing driven by the application of these technologies. The efforts are founded on the broad ability to gain insight from logistic, operational, and post-sale product data through advanced computational power and unprecedented network connectivity. Smart manufacturing is built on technologies such as artificial intelligence (AI) and machine learning (ML), cloud and edge computing, advanced modeling and simulation, Internet of Things, ontology applications for systems integration, and augmented reality capabilities. These technologies bring the ability to rapidly collect and analyze data, enabling the continuing refinement of performance based on principles of continuous improvement, ultimately leading to improved operational efficiency—thereby addressing the *financial outlook* barrier that SMM face in taking on sustainability projects.

The ISO standards highlighted here are based on continuous improvement principles, and their deployment helps to strengthen the organizational practice of this approach. With this common foundation, smart manufacturing systems can efficiently leverage pre-existing manufacturing paradigms such as lean manufacturing and quality management (Kibira, Morris, and Kumaraguru 2016) and can be harnessed for sustainability efforts (Kneib 2020). Early sustainable manufacturing standards efforts fill a gap between management estimation and the production models that are essential to incorporating environmental goals into continuous improvement (Brundage et al. 2018) and address the improvement of manufacturing operations from the sustainability perspective. Recent standards from ASTM E60.13 for modeling unit manufacturing processes support improved process control, intensity tracking, manufacturing system design, and metric reporting (Mani et al. 2016). Also evolving is ISO 20140 (ISO 2019) for evaluating energy efficiency across the manufacturing floor. ISO 20140 was analyzed using the Industrial Internet Reference Architecture to disaggregate the different stakeholder interests in the design of an environmental performance evaluation (EPE) system (Komoto et al. 2020). This analysis demonstrated the potential for production system designers to better model the environmental impacts of manufacturing.

We expect further guidance and innovation driven by these standards efforts to address the final barrier to sustainability: *organizational feasibility*. ASTM E60.13 standards, which enable the digital characterization of manufacturing through unit manufacturing process models, can support the ISO 20140 standards by providing more fine grain estimates of the performance of individual processes. In addition, research is ongoing to expand the capability of the ASTM E60.13 standards to improve the quality of life cycle inventory (LCI) datasets (Bernstein et al. 2020). These efforts will further improve estimations of production impacts for use in LCA, closing the loop from production back into the product design phase.

These standards and associated smart manufacturing technologies begin to address the possibilities for creating more sustainable manufacturing systems that optimize resources and minimize waste. Other opportunities exist. The integration of product lifecycle management technologies with manufacturing execution systems (MES), enterprise resource planning, and supply chain management data supports greater visibility into and planning for efficient use of resources (Bunse et al. 2011; Choi et al. 2016; Anderson 2019). As disparate management systems across the supply chain continue to integrate, common ontologies, metrics, and indicators will become more critical for optimization of supply chain performance and can be defined within these standard frameworks (Rodríguez-Enríquez et al. 2015). Most importantly these integration frameworks need to incorporate measurements and goals that support sustainability metrics.

Early adopter use-cases from Ericsson ("What Industry 4.0 Means for Manufacturing: Sustainability and Connectivity: Ericsson Tallinn Factory Case Study" 2019) and Rockwell ("The Journey Toward The Connected Enterprise" 2015) illustrate different aspects of smart manufacturing that resonate with our findings. Ericsson's recent campaign of investments in cellular-enabled IoT has led to high rates of return within its own sites. The optionality to economically explore other technologies, such as machine learning-powered preventative maintenance or AR-powered troubleshooting has enabled large realized and expected gains. Ericsson evaluated the impact of these projects across sites and dimensions, such as environmental, safety, and economic value. Rockwell also recently underwent an internal transformation towards IoT, or as they classify it, the "Connected Enterprise." Their highlights emphasize involving all the necessary stakeholders impacted by the newly connected systems. By involving stakeholders in the design and implementation phases, the benefits of expanded and accessible measurement capability have been readily appreciated. Overall, the campaign has led to higher productivity, quality, and customer response time. These case studies highlight the success of early adopters of such technologies. Similar results should be achievable for SMM. Recent MEP awards include a focus on these technologies to develop competency in deploying to SMM (NIST-MEP 2020).

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This study opens avenues for future research to propel SMM towards more sustainable practices. New metrics that address the coupling of sustainability objectives with standards-driven deployment may be engaged to better measure the interplay of these two approaches. MEP projects have already been initiated to address the adoption of smart manufacturing technologies and apply such approaches to improvements across sustainability-related metrics. As these experiences are collected and accumulate, they will provide a basis for future analysis to determine their success. The MEP program is home to a wealth of expertise surrounding manufacturing practices and corporate appetite for change. As mentioned, each MEP project is reviewed after its conclusion and metrics are collected on the performance of the project. This study was limited by metrics that MEP currently collects. This reporting mechanism could be harnessed to explore greater opportunities for engaging SMM towards sustainable development goals. For instance, new metrics may be developed to facilitate analysis of the interplay of such cross-functional efforts. Similarly, with the IAC data collection efforts, metrics reflecting the longer term impacts of the projects would be useful data points for reflecting the significance the centers' intervention efforts. In the educational realm, these findings can be significant for engineering and engineering management education to engrain sustainability objectives as standard practice across disciplines. In the social science realm, opportunities exist for exploring the implications of this evidence in light of confirmation bias and how to confront such bias to accelerate change.

This study indicates that experience is needed to better understand successful practices for improving manufacturing operation and also that data to validate that those practices are successful across both sustainability and business metrics will be needed to accelerate the rate of adoption. Without such metrics, SMM may be stalled in the adoption of sustainable practices by unsubstantiated expectations not grounded in data. Furthermore, evidence that a practice was successful—collected through vigilant reporting and analysis—may accelerate both the development of broadly deployable standards and the rate at which environmental impacts are reduced.

6. Conclusion

This study shows that revisiting reported barriers to sustainability can create significant opportunities for SMM of all sizes. Our interviews with IAC and MEP experts highlighted commonly reported views towards sustainability, including trade-offs between "growing the business" and sustainability, longer pay-back periods, and significant organizational barriers. These same findings were corroborated in the literature review; however, our interviews, supported by our analysis, also challenged the notion that sustainable investments deter both cost savings as well as growth, especially when founded on standards. The evidence shows that this conclusion can extend to even the smallest manufacturers, challenging the notion of feasibility (cultural, technical, or otherwise). Our refocused view of the barriers to sustainability for SMM indicated the following ways to capitalize on sustainability:

- Align management to a proactive view of sustainability within emerging supply chain pressures,
- Evaluate financial decisions holistically to identify opportunity costs, and
- Pursue technical guidance and standards for cross-organizational measurement.

This study also brings clarity to the relationship between SASB and technical standards from ISO and ASTM by highlighting the significance of standards in pursuing sustainability. The connection between financial materiality and standards-driven sustainability initiatives is apparent. The ubiquity of the ISO 14000 series among SASB reporting companies means that data-driven standards such as ISO 20140 and ASTM E60.13 series are well-positioned to connect environmental management with continuous improvement. In addition, they provide a basis for the data collection that will be needed for sustainability metrics reporting. We see an opportunity for manufacturers to implement initiatives based on the ISO 20140 and ASTM E60.13 series of standards where ISO 14001 and even ISO 9001 & 50001 groundwork is already in place. The prevalence of supply chain sustainability management in SASB standards, sustainability reports, roundtable discussions, and MEP data indicates that sustainability will be of growing importance to SMM within global supply chains.

In summary, this study identified reported barriers for SMM to pursue more sustainable practices, relying on open literature as well as experts in the field. These barriers were tested by analyzing data from historical records of sustainability projects across several years. The analysis demonstrated that the reported barriers have been shown to be surmountable. Enterprises that addressed the barriers actually showed net positive outcomes to their business in terms of return on investment and retained and increased sales. Our report explores the use of technology and standards referenced in the corporate sustainability reports of larger manufacturers. Referring to existing data, we found that these approaches also bring value for SMM. Standards that improve sustainability outcomes can be used to reduce the risk to SMM pursuing their own paths to sustainability. Figure 2 illustrates that these and other standards, that will support further progress towards more sustainable manufacturing, are growing in breadth and potential paving the way for future improvement across the industry.

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References

Anderson, Gregg. 2019. "Want to Get Serious About Sustainability? Use SASB's Standards to Inform ERM." Crowe. https://www.sasb.org/wp-content/uploads/2019/06/SASB-and-ERM-RISK-17019-009A-1.pdf.

Apparel Coalition. 2020. "Members – Sustainable Apparel Coalition." 2020. https://apparelcoalition.org/members/.

https://doi.org/10.1016/j.jclepro.2022.130589

Apple Newsroom. 2020. “Apple Commits to Be 100 Percent Carbon Neutral for Its Supply Chain and Products by 2030.” Press Release. Apple Newsroom. https://www.apple.com/newsroom/2020/07/apple-commits-to-be-100-percent-carbon-neutral-for-its-supply-chain-and-products-by-2030/.

ASME Open Research Forum. 2013. “ASME Sustainable Manufacturing: Preparing for a New Business Imperative.” Washington, DC: ASME.

Bai, Chunguang, Ahmet Satir, and Joseph Sarkis. 2019. “Investing in Lean Manufacturing Practices: An Environmental and Operational Perspective.” *International Journal of Production Research* 57 (4): 1037–51.

Beal, Douglas, Robert Eccles, Gerry Hansell, Rich Lesser, Shalini Unnikrishnan, Wendy Woods, and David Young. 2017. “Total Societal Impact: A New Lens for Strategy.” Boston Consulting Group. https://media-publications.bcg.com/BCG-Total-Societal-Impact-Oct-2017.pdf.

Bernstein, William Z., Melissa Tensa, Maxwell Praniewicz, Soonjo Kwon, and Devarajan Ramanujan. 2020. “An Automated Workflow for Integrating Environmental Sustainability Assessment into Parametric Part Design through Standard Reference Models.” *27th CIRP Life Cycle Engineering Conference (LCE2020)Advancing Life Cycle Engineering : From Technological Eco-Efficiency to Technology That Supports a World That Meets the Development Goals and the Absolute Sustainability* 90 (January): 102–8. https://doi.org/10.1016/j.procir.2020.02.058.

Brundage, Michael P., William Z. Bernstein, Steven Hoffenson, Qing Chang, Hidetaka Nishi, Timothy Kliks, and K. C. Morris. 2018. “Analyzing Environmental Sustainability Methods for Use Earlier in the Product Lifecycle.” *Journal of Cleaner Production* 187 (June): 877–92. https://doi.org/10.1016/j.jclepro.2018.03.187.

Bunse, Katharina, Matthias Vodicka, Paul Schönsleben, Marc Brülhart, and Frank O. Ernst. 2011. “Integrating Energy Efficiency Performance in Production Management – Gap Analysis between Industrial Needs and Scientific Literature.” *Journal of Cleaner Production* 19 (6–7): 667–79. https://doi.org/10.1016/j.jclepro.2010.11.011.

Bureau of Labor Statistics. n.d. “Number of Business Establishments by Size of Establishment in Selected Private Industries.” Accessed October 30, 2021. https://www.bls.gov/charts/county-employment-and-wages/establishments-by-size.htm.

Carley, Sanya, Jerry Jasinowski, Greg Glassley, Patrick Strahan, Shahzeen Attari, and Scott Shackelford. 2014. “Success Paths to Sustainable Manufacturing.” School of Public and Environmental Affairs Indiana University. https://oneill.indiana.edu/doc/research/sustainability-2014.pdf.

Choi, Sangsu, Kiwook Jung, Boonserm Kulvatunyou, and Kc Morris. 2016. “An Analysis of Technologies and Standards for Designing Smart Manufacturing Systems.” *Journal of*

Research of the National Institute of Standards and Technology 121 (September): 422. https://doi.org/10.6028/jres.121.021.

Delmas, Magali A., and Sanja Pekovic. 2013. "Environmental Standards and Labor Productivity: Understanding the Mechanisms That Sustain Sustainability." *Journal of Organizational Behavior* 34 (2): 230–52. https://doi.org/10.1002/job.1827.

Despeisse, M., F. Mbaye, P. D. Ball, and A. Levers. 2012. "The Emergence of Sustainable Manufacturing Practices." *Production Planning & Control* 23 (5): 354–76. https://doi.org/10.1080/09537287.2011.555425.

Eccles, Robert G. 2020. "Crunch Time: Global Standard Setters Set The Scene For Comprehensive Corporate Reporting." *Forbes*, October. https://www.forbes.com/sites/bobeccles/2020/10/08/crunch-time-global-standard-setters-set-the-scene-for-comprehensive-corporate-reporting/?sh=53b3a8c61c33.

Haapala, Karl R., Fu Zhao, Jaime Camelio, John W. Sutherland, Steven J. Skerlos, David A. Dornfeld, I. S. Jawahir, Andres F. Clarens, and Jeremy L. Rickli. 2013. "A Review of Engineering Research in Sustainable Manufacturing." *Journal of Manufacturing Science and Engineering* 135 (041013). https://doi.org/10.1115/1.4024040.

Hale, Jon. 2019. "Enhancement to Sustainability Rating Emphasizes Material ESG Risk." *Morningstar, Inc.*, November 8, 2019. https://www.morningstar.com/articles/954595/enhancement-to-sustainability-rating-emphasizes-material-esg-risk.

IAC University. 2020. "IAC: Industrial Assessment Centers." IAC University. 2020. https://iac.university/.

Iacurci, Greg. 2020. "Money Moving into Environmental Funds Shatters Previous Record." CNBC. January 14, 2020. https://www.cnbc.com/2020/01/14/esg-funds-see-record-inflows-in-2019.html.

"Industrial Assessment Centers." 2020. Energy.Gov. 2020. https://www.energy.gov/eere/amo/industrial-assessment-centers-iacs.

Institution for Responsible Business Conduct. 2020. "OECD Guidelines - Business Conduct." 2020. https://businessconduct.dk/oecd-guidelines.

ISO. 2019. "ISO 20140-1:2019: Automation Systems and Integration — Evaluating Energy Efficiency and Other Factors of Manufacturing Systems That Influence the Environment — Part 1: Overview and General Principles." https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/93/69358.html.

Jackson-Moore, Will, Case, Phil, Bobin Emilie, and Joukje Janssen. 2019. "Older and Wiser: Is Responsible Investment Coming of Age?" Private Equity Responsible Investment Survey 2019. PwC. https://www.pwc.com/gx/en/services/sustainability/publications/private-equity-and-the-responsible-investment-survey.html.

Joung, Che B., John Carrell, Prabir Sarkar, and Shaw C. Feng. 2013. "Categorization of Indicators for Sustainable Manufacturing." *Ecological Indicators* 24 (January): 148–57. https://doi.org/10.1016/j.ecolind.2012.05.030.

Khan, Mozaffar, George Serafeim, and Aaron Yoon. 2016. "Corporate Sustainability: First Evidence on Materiality." *Accounting Review* 91 (6): 1697–1724.

Kibira, Deogratias, Kc Morris, and Senthilkumaran Kumaraguru. 2016. "Methods and Tools for Performance Assurance of Smart Manufacturing Systems." *Journal of Research of the National Institute of Standards and Technology* 121 (June): 287. https://doi.org/10.6028/jres.121.013.

Kneib, Maria Negron. 2020. "Intersecting Sustainability: ESG and Smart Manufacturing Trends." Trends Report. Manufacturers Alliance for Productivity and Innovation (MAPI) Foundation.

Komoto, Hitoshi, William Z. Bernstein, Soonjo Kwon, and Fumihiko Kimura. 2020. "Standardizing Environmental Performance Evaluation of Manufacturing Systems through ISO 20140." *27th CIRP Life Cycle Engineering Conference (LCE2020)Advancing Life Cycle Engineering : From Technological Eco-Efficiency to Technology That Supports a World That Meets the Development Goals and the Absolute Sustainability* 90 (January): 528–33. https://doi.org/10.1016/j.procir.2020.02.043.

"Letter to US Securities and Exchange Commission." 2019, October 17, 2019. https://www.sec.gov/comments/s7-11-19/s71119-6313644-193668.pdf.

Lu, Yan, Katherine C. Morris, and Simon P. Frechette. 2016. "Current Standards Landscape for Smart Manufacturing Systems." https://www.nist.gov/publications/current-standards-landscape-smart-manufacturing-systems.

Lyndenberg, Steve, and David Wood. 2010. "How to Read a Corporate Social Responsibility Report: A User's Guide." Report, News and Publications. Sustainability Reporting. Boston College, Center for Corporate Citizenship: Institute for Responsible Investment. https://iri.hks.harvard.edu/files/iri/files/how_to_read_a_corporate_social_responsibility_report.pdf.

Mani, Mahesh, Jon Larborn, Bjorn Johansson, Kevin W. Lyons, and K. C. Morris. 2016. "Standard Representations for Sustainability Characterization of Industrial Processes." *Journal of Manufacturing Science and Engineering* 138 (10). https://doi.org/10.1115/1.4033922.

https://doi.org/10.1016/j.jclepro.2022.130589

Marra, Manuela, Carla Di Biccari, Mariangela Lazoi, and Angelo Corallo. 2018. “A Gap Analysis Methodology for Product Lifecycle Management Assessment.” *IEEE Transactions on Engineering Management* 65 (1): 155–67. https://doi.org/10.1109/TEM.2017.2762401.

Matthews, Chris. 2019. “The S&P 500 Is More Dependent on Manufacturing than You Think.” *Market Watch*, Investing, , September. https://www.marketwatch.com/story/the-sp-500-is-more-dependent-on-manufacturing-than-you-think-2019-09-11.

“MEP National Network Success Stories.” 2019. NIST Manufacturing Extension Partnership (MEP). May 17, 2019. https://www.nist.gov/mep/successstories.

Murphy, Christopher. 2002. “The Profitable Correlation Between Environmental and Financial Performance: A Review of the Research.” Light Green Advisors, Inc.

Naden, Clare. 2020. “Temperatures Rising.” *ISO* (blog). December 18, 2020. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/news/2020/12/Ref2607.html.

NIST-MEP. 2020. “NIST Awards $11 Million to MEP Centers in 10 States.” NIST Updates. September 21, 2020. https://www.nist.gov/news-events/news/2020/09/nist-awards-11-million-mep-centers-10-states.

Organisation for Economic Co-operation and Development. 2021. “About Sustainable Manufacturing - OECD.” 2021. https://www.oecd.org/innovation/green/toolkit/aboutsustainablemanufacturingandthetoolkit.htm.

Oxford Analytica. 2021. “The Future of Sustainability Reporting Standards.” https://assets.ey.com/content/dam/ey-sites/ey-com/en_gl/topics/sustainability/ey-the-future-of-sustainability-reporting-standards-june-2021.pdf.

Polman, Paul, and CB Bhattacharya. 2016. “Engaging Employees to Create a Sustainable Business.” *Stanford Social Innovation Review*, no. Fall 2016 (September). https://ssir.org/articles/entry/engaging_employees_to_create_a_sustainable_business.

Prakash, Nives Dolsak and Aseem. 2020. “Unilever’s Climate Plan: Emissions From Supply Chain And Consumers Are The Real Challenge.” *Forbes*, June. https://www.forbes.com/sites/prakashdolsak/2020/06/18/unilevers-climate-plan-emissions-from-supply-chain-and-consumers-are-the-real-challenge/.

Pucker, Kenneth P. 2021. “Overselling Sustainability Reporting.” *Harvard Business Review*, May. https://hbr.org/2021/05/overselling-sustainability-reporting.

Rodríguez-Enríquez, Cristian Aarón, Giner Alor-Hernández, Cuauhtémoc Sánchez-Ramírez, and Guillermo Córtes-Robles. 2015. “Supply chain knowledge management: A linked data-based approach using SKOS." *Dyna; Bogota* 82 (194): 27. https://doi.org/DOI: http://dx.doi.org/10.15446/dyna.v82n194.54463.

Sarkar, Prabir, Che Bong Joung, John Carrell, and Shaw C. Feng. 2012. "Sustainable Manufacturing Indicator Repository." In , 943–50. American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/DETC2011-47491.

"SASB Materiality Map." 2018. 2018. https://materiality.sasb.org/.

"SASB Reporters." 2018. SASB. 2018. https://www.sasb.org/company-use/sasb-reporters/.

Sinha, Alok. 2010. "Sustainability Certifications and Standards: Making Sense of the Maze for Your Business." Strategic Sustainability Consulting. http://www.sustainabilityconsulting.com/extra-resources/sustainability-certifications-and-standards.html.

Smith, Brad. 2020. "Microsoft Will Be Carbon Negative by 2030." *The Official Microsoft Blog* (blog). January 16, 2020. https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/.

Smith, Elliot. 2020. "The Numbers Suggest the Green Investing 'mega Trend' Is Here to Stay." CNBC. February 14, 2020. https://www.cnbc.com/2020/02/14/esg-investing-numbers-suggest-green-investing-mega-trend-is-here.html.

"Sustainability Accounting Standards Board." 2018. Sustainability Accounting Standards Board. 2018. https://www.sasb.org/.

"The Journey Toward The Connected Enterprise." 2015. Rockwell Automation.

"The Sustainability Consortium." 2020. The Sustainability Consortium. 2020. https://www.sustainabilityconsortium.org/about/.

Thomas, Douglas. 2020. "The Manufacturing Cost Guide: A Primer - Version 1.0." https://www.nist.gov/publications/manufacturing-cost-guide-primer-version-10.

Trotta, Maria Giovanna. 2010. "Product Lifecycle Management: Sustainability and Knowledge Management as Keys in a Complex System of Product Development." *Journal of Industrial Engineering and Management*. https://doi.org/doi:http://dx.doi.org/10.3926/jiem..v3n2.p309-322.

United Nations. 2015. "Transforming Our World: The 2030 Agenda for Sustainable Development." A/RES/70/1. United Nations. https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981.

https://doi.org/10.1016/j.jclepro.2022.130589

US Department of Energy. 2021. “50001 Ready Program | Better Buildings Initiative.” 2021. https://betterbuildingssolutioncenter.energy.gov/iso-50001/50001Ready.

Wanner, Jonas, and Christian Janiesch. 2019. “Big Data Analytics in Sustainability Reports: An Analysis Based on the Perceived Credibility of Corporate Published Information.” *Business Research* 12 (1): 143–73. https://doi.org/10.1007/s40685-019-0088-4.

“What Industry 4.0 Means for Manufacturing: Sustainability and Connectivity: Ericsson Tallinn Factory Case Study.” 2019. Ericsson.com: Ericsson. https://www.ericsson.com/assets/local/internet-of-things/industry-4.0/docs/ericsson-tallinn-factory_case_study.pdf.

Whelan, Tensie, and Carly Fink. 2016. “The Comprehensive Business Case for Sustainability.” *Harvard Business Review*, October. https://hbr.org/2016/10/the-comprehensive-business-case-for-sustainability.

World Resources Institute and World Business Council for Sustainable Development. 2004. “GHG Protocol: A Corporate Accounting and Reporting Standard: Revised Edition.” Greenhouse Gas Protocol Organization. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.