A review of:

Materials Sustainability Frameworks

An Oregon perspective

State of Oregon
DEQ Department of Environmental Quality

A report from the Materials Management Program

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Materials Management Program

Materials management takes a holistic view of environmental impacts across the full life cycle of materials, as well as actions that can be taken to reduce those impacts. It includes resource extraction and use of recovered materials, the design and production of materials, their use, and end-of-life management, including solid waste disposal and recovery.

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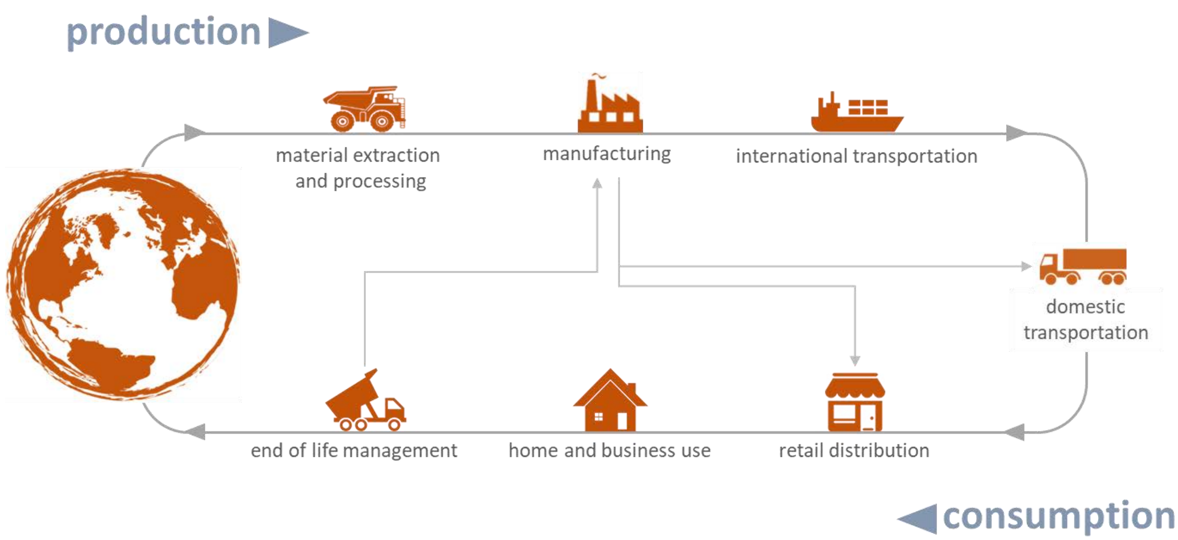
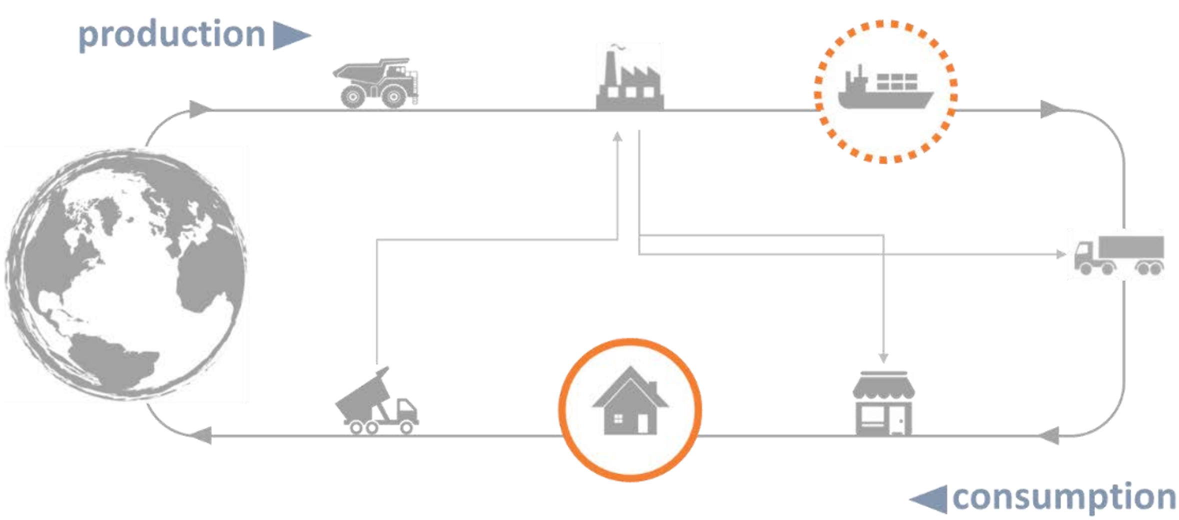




Solid circle: a given sustainability framework is presently fully operational within the life cycle stage.
Dotted circle: a given sustainability framework is marginally operational within the life cycle stage

Synopsis

Competition is the driving force behind industrial and economic activities worldwide. This competitive drive for ever-increasing economic growth puts pressures on ecosystems and human systems, not just in the pure resource demand sense, but also on social fabrics and international relations. Sustainability efforts are a response to counter the effects of global human demand on the planet's natural systems. The Sustainable Development Goals (SDGs) embody global aspirations for environmentally and socially equitable economic development.

Sustainability efforts are guided by an underlying assumption that the actions improve the environmental and social aspects of the industrial and economic activities. While that indeed may be the premise, sustainability efforts, particularly those related to material stewardship, are fragmented into various sustainability frameworks. For broader impact reduction that is necessary to achieve sustainable development – "meeting the needs of the present without compromising the ability of future generations to meet their own needs," a more cooperative approach is needed.

Practitioners of different sustainability frameworks therefore must agree first that, regardless of the specific tactics of their framework, we are embarked on a journey to the same end state, to counter growing environmental stresses brought on by a constant demand on the natural systems for material inputs. Practitioners of each approach must recognize mutually that the end state we seek is similar – a world with greater materials stewardship or conservation that protects the environment, and enhances the wellbeing of humans and the diversity of flora and fauna on Earth.

Unfortunately, among practitioners of different sustainability frameworks such as those listed in the call box there exists significant knowledge silos. These knowledge silos prevent cross pollination of ideas even at the concept level where there exists real commonalities. The competitive or protective nature of implementation thus leads to a great deal of system churn within the framework, leaving the

Frameworks reviewed

Lean Thinking offers a long-standing structure for reducing and eliminating waste of all kinds from processes and operations.

Pollution Prevention is a mechanism to systematically reduce and eliminate pollution from processes and operations.

Zero Waste is principally concerned with material recovery from the municipal solid waste stream for secondary use.

Circular Economy advocates for closed material loops to maximize their best and highest use towards a resilient material economy.

Sustainable Materials Management is a whole system or life cycle-based approach to reduce the environmental burdens associated with material consumption.

proverbial dots between different approaches unconnected. A cooperative model simply asks to look across the fence and see what might be applicable. Could the strengths of different sustainability frameworks be leveraged to advance common outcomes?

Fortunately, there exists a strong body of scientific understanding related to materials and the systems that make, use and recover them in the realm of Industrial Ecology. In addition, significant understanding of design for environment, tried and tested on-the-ground implementation techniques for remediation, mitigation, analytics and measurement also exists. The challenge is in learning across areas of implementation. This is a problem of pedagogy, an issue of operational protectionism that may be an offshoot of predominantly competitive approaches. In this paper we attempt to show that there is a great deal of ambition, intention, and conviction to improve the environmental state of the planet, particularly as related to reducing the impacts of materials. The missing piece may be a shift towards cooperative and collaborative approaches for sustainability efforts. It is said that the solution to a problem will not come about by applying the same mindset that creates it. If so, we must be open to the argument that if competition for resources in a globalized economy has generated the environmental woes of today, then we must consider that competition among sustainability activists and adherents attempting to buttress against that tide might not be a good thing. A fragmented approach to sustainability is not likely to achieve sustained long-term benefits.

Competition among practitioners of various schools of thoughts is not necessarily the best approach on the journey to a sustainable future that each path is meant to achieve. Improving environmental and social dimensions is not a zero sum game, and the efforts of each approach must contribute to a cooperative approach that builds on the strengths of different practices. Such a cooperative approach may be a stronger strategic mechanism to buttress against the serious environmental degradation and social inequities created by the growth-driven economic mandate.

Ever-increasing consumption cannot be the path forward as planetary resilience is steadily destabilized. In the same vein, competition among various sustainability frameworks cannot be the path forward for environmental stewardship at scale.

This paper reviews several sustainability frameworks including Zero Waste, Circular Economy, Pollution Prevention and Sustainable Materials Management.

The desire for organizing frameworks of material sustainability stems from an acknowledgement, both explicit and tacit, that all material choices by industry, in society, and by individuals come with burdens on the environment writ large. These burdens in turn affect human wellbeing and our ability to engage in meaningful economic activities. It also affects all other life on the planet. It may be time to channel the efforts towards material sustainability in a cooperative model among the various philosophical approaches of these practice areas.

A life cycle or whole system approach illustrated in Figure 1 can offer a convenient backdrop for a consistent view of the applicability, deficiencies and opportunities to leverage the efforts and strengths of other practices.

This paper superimposes the theoretical and practical practices of the listed frameworks on to the material life cycle. The life cycle lens offers a unifying structure to view the material flows starting with extractions or harvests from the earth, production and distribution, use, recovery

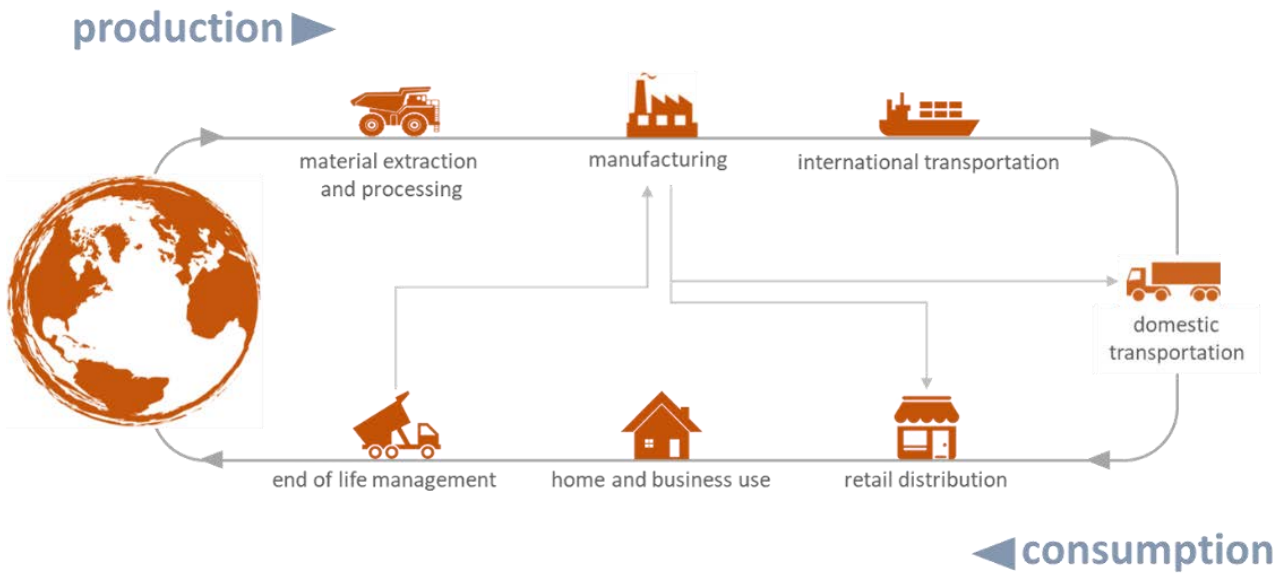


Figure 1 Generic life cycle of materials

and final disposal. The systematic life cycle perspective allows for a common platform upon which sustainability frameworks with different focus areas can be observed to find opportunities for cooperation and collaboration.

Why do materials matter?

Materials, from elemental chemicals to complex formulated and assembled products, are the base input into the economy. The vast array of materials in the global economy flow from points of extraction through multiple processing and manufacturing steps into the distribution networks for use by society, until ultimately discarded. Each step of this basic life cycle of materials contributes environmental and social stresses affecting every living thing on the planet. The implication of the environmental burdens are evidenced in myriad forms across the planet from climate shifts, diminished land quality, species decline, water scarcity, and more.

Here in Oregon, the consumption of (non-fuel) materials contributes 41 percent of the state's consumption-based greenhouse gas emissions[1]. Understanding and working to offset these stresses requires continuous efforts and diligence. All the frameworks reviewed in this paper work on material issues in different capacities and styles, and contribute to improving the overall

[1] For additional details see: Consumption-based Greenhouse Gas Emissions Inventory for Oregon https://www.oregon.gov/deq/mm/Pages/Consumption-based-GHG.aspx

environmental outcomes. A cooperative approach whereby practitioners of each framework leverages the knowledge, experience, data and analysis of the others may enhance the overall common bottom line – environmental stewardship via better management of industrial processes and material consumption.

Materials and Sustainable Development Goals

The Sustainable Development Goals (SDGs) emphasize the placement and priority of economic activities within social constructs, which in turn are expected to function within planetary boundaries. This dependence of human enterprises – social and commercial – on the living systems is often undervalued by the more narrowly focused sustainability initiatives and frameworks described in this paper, the focus often being economic growth or environmental mitigation and adaptation. The SDG construct is aligned with life cycle thinking and planetary boundary dialogues including conversations that focus on the carrying capacities of ecosystems and long term resiliency. The SDGs provide a big picture vision for sustainability into which the frameworks reviewed herein are contributing and can strengthen the long-term outcomes of the SDGs. Those contributions may be enhanced via a cooperative model, as the focus areas of the reviewed frameworks tend to be limited to subsets of human activities – principally those concerning the economy. At present the frameworks of interest (see Table 1) operate independently as knowledge silos with minimal crossover in activities, cross pollination of ideas and learning to leapfrog towards long-term material sustainability and environmental stewardship.

Summary of Frameworks

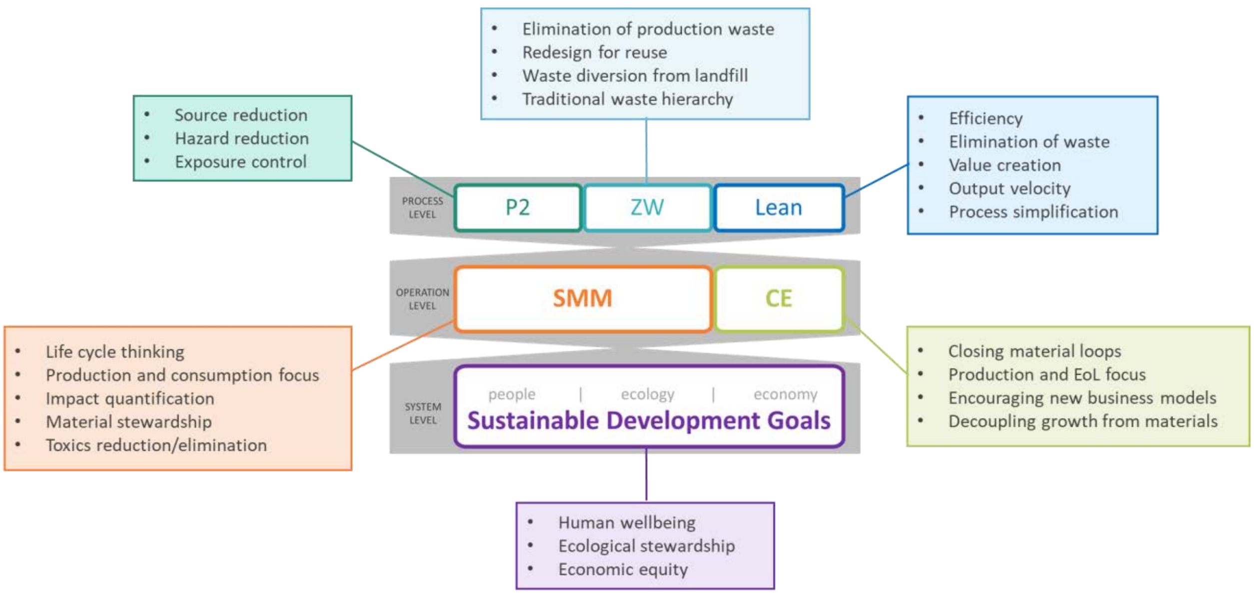
Table 1 Summary of frameworks reviewed

Framework	Sustainability Focus (environment, social, economy)	Principles	Strengths	Life Cycle Phases (applicability)	Life Cycle Phases (currently applied)
Lean Thinking (Lean) Elimination of wastes from business operations and production	Economy – production and operational processes	Map process to maximize value through considered and continuous improvement	Systematic process evaluation	Applicable and applied across all stages of production.	Applied across all stages of production and operation by select entities/businesses.
Pollution Prevention (P2) Avoidance of pollution via process evaluation and end-of-pipe regulatory approaches for production	Environment – pollution from production processes	Source reduction, recovery, treatment and managed disposal	Systematic process evaluation and end of pipe emissions controls	Applicable and applied across most stages of the material life cycle from extraction to disposal.	Applied across all stages of production and distribution via voluntary and legislative means.
Zero Waste (ZW) Solid waste disposal avoidance, primarily via recycling and composting	Environment – solid waste recovery	Source reduction, closed loops, reuse, recycle and managed disposal	Recycling advocacy	Applicable across most life cycle stages particularly production, retail and in home and business.	Applied principally for the solid waste management with an emphasis on recycling, and material diversion from landfill.
Circular Economy (CE) Business growth via material circularity (recovery, closed loops, and redesign)	Economy – design, production and material end of life	Preserve and enhance natural capital, create material circularity, design	Convening diverse stakeholders towards closed material loop thinking	Applicable across all stages of the material life cycle from extraction to disposal.	Presently significant focus on recycling and closing material loops. Evolving discourse about wholesale material redesign.
Sustainable Materials Management (SMM) Reduction of environmental burdens associated with making and using materials	Environment – measurable impact reductions throughout the material life cycle	Preserve natural capital, reduce environmental burdens, maintain materials at their best and highest use	Considered material investigations using life cycle based measurement, data, analysis	Applicable across all stages of the material life cycle from extraction to disposal	Significant emphasis on life cycle impacts with a strong emphasis on recovering high impact materials. Developing emphasis on upstream stages.

Frameworks Map

The Organization for Economic Co-operation and Development (OECD) has been developing and promulgating international policies aimed at preventing and reducing waste generation and managing the residues in an environmentally sound manner since the 1980s. The OECD concluded that it has become evident that waste minimization policies, which address only end of life of products and materials, are not effective in reducing the increasing amounts of waste associated with economic activity and material consumption. This accentuates the need for creative, far-sighted and integrated solutions, using life cycle thinking to reduce the negative environmental impacts of materials in a cost-effective manner (OECD, 2017).

Figure 2 expresses how the various frameworks might operate in a cooperative manner whereby increasing the efficacy of actions towards buttressing against the growing environmental and social burdens of material consumption worldwide. Applying whole system or



P2: Pollution Prevention, ZW: Zero Waste, SMM: Sustainable Materials Management, CE: Circular Economy

Figure 2 Relationships and linkages among sustainability frameworks

life cycle thinking[2] to the material problem can unify the actions undertaken by different sustainability frameworks to enhance the overall environmental outcomes. A cooperative approach across disciplines of frameworks such as Lean Thinking, Pollution Prevention and Zero Waste, can dramatically alter the reach of the action taken by practitioners within each framework. For example, the process level efforts of Lean Thinking (eliminating various waste

[2] Life cycle thinking is about going beyond one stage of the life cycle (such as solid waste disposal, or production site manufacturing processes) to include environmental, social and economic impacts of a product over its entire life cycle. The construct offers a shift in perspective from individual items to the entire system that enables its creation, use and discard. Life cycle thinking is different from life cycle assessment (LCA). While life cycle thinking is the approach to visualize system wide sustainability, LCA offers the mechanism for quantitatively evaluating, measuring and tracking changes in specific parts, actions in the system.

types), Zero Waste (avoiding high-value materials from being discarded) and Pollution Prevention actions are complementary approaches and may benefit from best practices from the respective professions. There may be significant benefits from an environmental lens to leverage the knowledge build up from the framework silos to enhance the respective fields. Figure 2 shows possible opportunities for coordinating various agendas towards the common goal of reducing environmental impacts, improving material stewardship, and enhancing wellbeing of humans and the biosphere.

The efficiency approach of Lean Thinking and Zero Waste combined with the prevention approach of Pollution Prevention can serve as best practices for larger frameworks such as Circular Economy and Sustainable Materials Management. Both Circular Economy and Sustainable Materials Management can in turn support the material aspects of human development and long term resilience agenda of the Sustainable Development Goals.

Overview

It is fairly easy to appreciate the importance of materials in every aspect of human enterprise, particularly in the form of basic material wellbeing – food, shelter, clothing, energy, safety; the list is long. Material consumption in the global economy is steadily rising and signs of stress on living systems are correspondingly growing in the form of climate change, freshwater demand, habitat fragmentation, marine debris, and dramatic chemical pollution in many forms (toxics, overloading of waterways with nutrients, etc.); again the list is long. Long term resilience hinges on sustainable use of materials in all their forms – from base elements to formulated chemistries and complex assemblies.

In considering what framework best advances material sustainability, it is important to turn first to the guidance provided by the United Nations. The foundation of global sustainability efforts is the oft-quoted definition that sustainable development ***"meets the needs of the present without compromising the ability of future generations to meet their own needs."*** (World Commission on Environment and Development, 1987). The United Nations' sustainable development priorities are organized as the Sustainable Development Goals[3]. Also known as the Global Goals, they represent a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity. The 17 Global Goals address climate change, economic inequality, innovation, sustainable consumption, peace and justice, among other priorities. The goals are interconnected – often the key to success on one will involve tackling issues more commonly associated with another (UNDP, 2018). The Global Goals are

[3] See Sustainable Development Knowledge Platform https://sustainabledevelopment.un.org/

presented here as a grounding for sustainability activities, providing the overarching structure for sustainable development worldwide.

Figure 3 United Nations' Sustainable Development Goals (UNDP, 2018)

The Sustainable Development Goals emphasize the placement and priority of economic activities within social constructs, which in turn function within planetary boundaries. This dependence of human enterprises – social and commercial – on the living systems is often undervalued by the more narrowly focused sustainability initiatives and frameworks described in this paper. The Sustainable Development Goals construct is entirely aligned with life cycle

Figure 4 Sustainable Development Goals Hierarchy (UNDP, 2018)

thinking and planetary boundary dialogues including conversations that focus on the carrying capacities of ecosystems and long-term resiliency.

The 17 Global Goals listed in Figure 3 represent critical fronts for human development with safeguards for ecological wellbeing to meet the temporal aspect of the original sustainable development charter – that the needs of the generations to come are not compromised. These core goals and values represent the highest manifestation of sustainable development and offer a holistic perspective to practitioners using the material sustainability frameworks described here. The program "has a key role in supporting countries to make this vision a reality—putting societies on a sustainable development pathway, managing risk and enhancing resilience, and advancing prosperity and wellbeing" (UNDP, 2016).

Sustainable Development Goals do not explicitly apply a life cycle perspective, and yet the 17 Global Goals touch the material life cycle in significant and relevant ways with critical touch points for human development, environmental protection and economic fairness. The Sustainable Development Goals therefore can be argued to plug into the material life cycle in a holistic manner – perhaps more so than any single or combination of frameworks considered in this report. The construct of the Sustainable Development Goals is human-centric; it places economic actions and, by extension, materials in the context of human development, and not as an inherent good for their own sake, or solely as an enabling agent for economic activities writ large.

Frameworks for Material Sustainability

What sustainability principles should guide our use of materials? The work of the United Nations serves as an important backstop, yet over the past 30 years, sustainable development has steadily evolved and the notion of what is sustainable along with it. In the U.S., for example, *sustainable development* is rarely mentioned outside of the context of foreign aid or development organizations. Instead, *sustainability* is commonly used to refer to a one-dimensional framework for evaluating relative environmental impact. Options that are perceived to be less bad for the environment are often referred to as *sustainable* regardless of their actual environmental impacts, not to mention social or economic implications.

Table 2 shows materials specific frameworks that may fit the *sustainability* bill including Lean Thinking (lean)[4], Pollution Prevention (P2)[5], Zero Waste (ZW)[6], Circular Economy (CE)[7], and Sustainable Materials Management (SMM)[8].

[4] See Lean Enterprise Institute https://www.lean.org/

[5] See USEPA Pollution Prevention (P2) https://www.epa.gov/p2

[6] See Zero Waste International Alliance http://zwia.org/

[7] See The Ellen MacArthur Foundation https://www.ellenmacarthurfoundation.org/circular-economy

[8] See USEPA, Sustainable Materials Management https://www.epa.gov/smm. Also see OECD, Sustainable Materials Management http://www.oecd.org/env/waste/smm.htm, and Oregon DEQ, 2012. Materials Management in Oregon 2050 Vision and framework for Action. http://www.oregon.gov/deq/FilterDocs/MManagementOR.pdf

Table 2 Sustainability focus of different frameworks

Framework	Principle Sustainability Focus Area		
	Biosphere (Environment)	Society	Economy
Lean Thinking (lean)			Business operations and production
Pollution Prevention (P2)	Avoidance of pollution via proactive preventive beyond compliance approaches		
Zero Waste (ZW)	Solid waste reduction/avoidance primarily via recycling and composting		Secondary (recycled) materials market
Circular Economy (CE)			Business growth via material circularity (recovery, closed loops, and redesign)
Sustainable Materials Management (SMM)	Reduction of environmental burdens associated with making and using materials		Secondary (recycled) materials market

All of these frameworks focus on materials in their myriad[9] forms as they flow through society, and they attempt to reduce environmental burdens while stimulating economic activities that are less environmentally damaging. Each framework has a body of expertise and best practices that can be leveraged by the others. In particular the sum of research amassed under the Industrial Ecology[10] banner is equally available to all the frameworks discussed herein.

Objectives

This paper is an attempt to clarify the potential scope, potential limitations and practical application of each framework by identifying the areas of overlap and opportunity. This is done

[9] 'Materials' as used in this document refers to both macro materials, such as food and materials with important structural properties such as concrete, plastics, metals etcetera, and micro materials (i.e., chemicals) with important functional properties.

[10] Industrial ecology is the study of the physical, chemical, and biological interactions and interrelationships both within and between industrial and ecological systems. Industrial ecology attempts to provide a conceptual approach for understanding the impacts of industrial systems on the environment (Garner & Keoleian, 1995). Further, within industrial ecology many approaches are utilized. This includes life cycle assessment, green chemistry, design thinking, systems mapping, materials flow analyses etc.; all of which are available to all other frameworks discussed in this paper. Industrial ecology, therefore can be viewed akin to other –ology such as biology or entomology – as a study of industrial systems in the same manner as biology or entomology is the study of living things and insects respectively.

in the spirit of cross-pollination of ideas and philosophies in support of deeper underlying goals of sustainable development – specifically in the context of responsible management of material production and consumption to lower environmental burdens, and improve the wellbeing of people and planet.

Two objectives inform this review:

> ***The sustainable management of materials must be prioritized for the goal of reducing environmental impacts across the whole life cycle of materials, not just of solid waste management.***
>
> ***Opportunities exist to better integrate knowledge and expertise between and across various material sustainability frameworks.***

To ground the materials discussion, the analysis draws on the well-established solid waste management hierarchy (see Figure 5) as an important touchstone. While it may not reflect opportunities across the entire life cycle, it can serve as a useful reference for many of the frameworks examined here. In addition, the United Nation's Sustainable Development Goals (UN SDG) provide an important foundation to further ground the overall discussion within the ecological, social and economic realms.

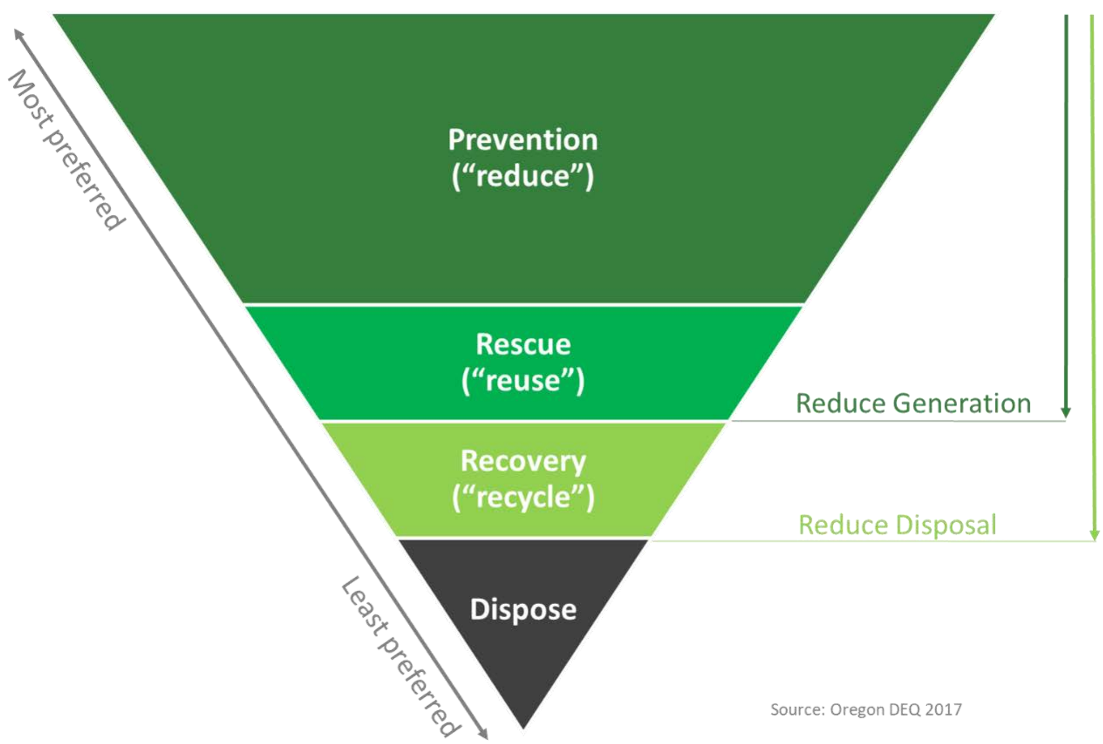


Figure 5 Waste reduction hierarchy

Life Cycles of Materials

Today's globally-connected economies rely on resource inputs from practically all regions of the planet interlinking the materials supply networks at the root level from resource extraction through discard management. The life cycle perspective is a useful mechanism to understand how societies use materials and the implications to the planet's biotic and abiotic systems[11] resulting from that material demand. Figure 6 depicts a generic life cycle of materials or products starting with extracting resources from the planet, processing them into materials to be used in the manufacturing of goods, transporting them, distributing and selling them, using them and ultimately, discarding them at the end of their useful life. Sustainable development's underlying balancing act of meeting the needs of the current generation while maintaining the planet's ability to sustain itself for generations to come is deeply intertwined with the life cycle of materials depicted in this illustration.

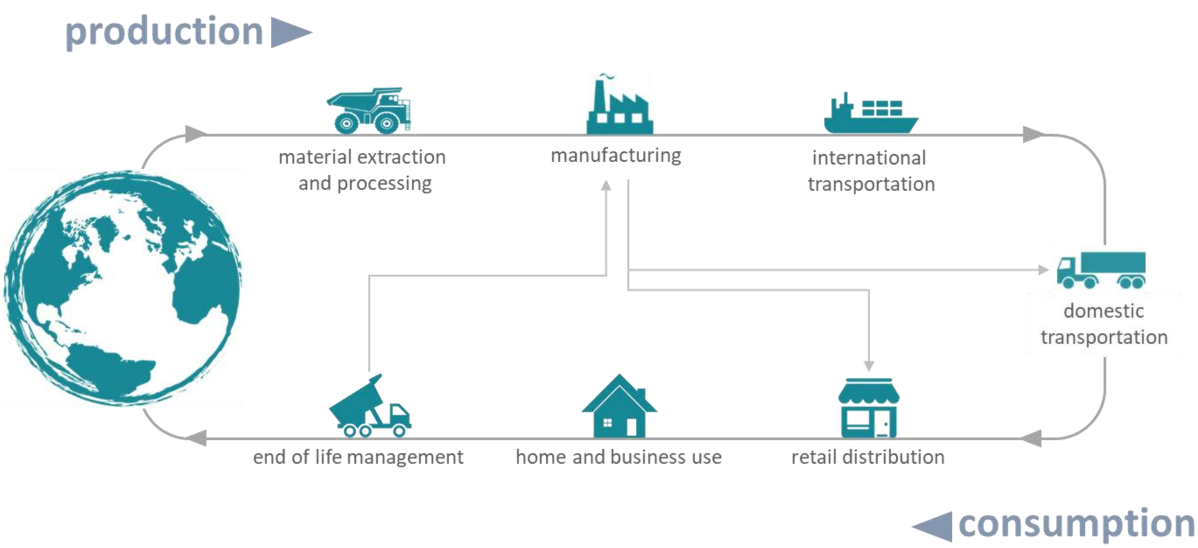


Figure 6 Generic life cycle of materials and products

Benefits and Burdens

The wellbeing and livelihoods of people of all walks of life are directly and indirectly touched by the life cycle of materials. At the root level all global economic activities are fueled by substances extracted from the planet and converted into materials that are used to make things that people rely on for everyday activities from the mundane to the miraculous. Understanding material life cycles and the burdens imposed on the planet is essential for maintaining a balance between the ecological, social and economic aspects of the material web. Planetary resilience is at the heart of sustainable development, particularly with regards to the long-term "ability of

[11] Biotic refers to the living components of ecosystems, while abiotic refers to the non-living components of ecosystems.

future generations to meet their own needs" (World Commission on Environment and Development, 1987).

The simplified illustration in Figure 6 shows the flow of materials from an industrial perspective. Materials originating from the planet are often returned to the natural systems of the planet in myriad forms that are often in a very different state from that which was extracted from the Earth. This process imposes emissions and stresses on air, land and water that affect the ecological wellbeing which sustains all the biota including humans. The life cycle perspective allows us to parse activities within each step of the life cycle to identify areas of influence for change.

The burdens associated with material extraction, product manufacture, distribution, use and discard are not distributed evenly throughout the life cycle of material flow. The front part – extraction through manufacture and distribution – often imparts a significant majority of environmental burdens of a product system. The end-of-life treatment, though essential, typically has relatively small impacts and plays a minor role to obviate the impacts of the industrial systems. Focusing on the end-of-life as a means to sustainability offers small rewards compared to what is possible by leveraging the opportunities starting at extraction, production, and use.

A leading method for estimating environmental impacts of materials is life cycle assessment (LCA) [12]. LCA is a technique to assess environmental impacts associated with some of or ideally all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recovery. Designers can use LCA to understand the parts and processes involved in making their products. Companies can use it to set priorities, track progress and report information to their value networks. Researchers use LCA to quantify the current state and probe what-if scenarios of emerging issues and technologies. Policymakers can apply it to better understand environmental outcomes and set proactive science-based targets and goals. LCA is used by educators to help students connect the dots between disparate industrial activities within globally distributed economies and understand the dynamics between production, consumption, and disposal.

It is critical to appreciate that while LCA is ideally suited to describe multiple impact areas across the life cycle of industrial activities, it is not a one size fits all situation tool. Some impact areas including human health, toxicity, and burdens associated with litter and marine debris are not evaluated well by LCA, if at all. It is therefore necessary to build and use a diverse toolkit to bridge the information gaps across practice areas. Cooperation and collaboration are essential across practice areas to breakdown knowledge silos.

[12] Life cycle assessment or LCA is a systematic approach to estimate environmental burdens associated with drawing resources from the Earth, transforming them into usable technical materials, making items from them, distributing the items, using them and ultimately dealing with the remaining solid waste via different waste treatment and recycling activities. LCA is governed by several international standards that provide guidance about various aspects of accounting for the different processing and materials needed to make, use, and end-of-life treatment of a product. LCA is a foundational analytical approach to estimate environmental burdens of industrial systems and allows fair comparisons between different functionally equivalent systems. To learn more see: http://www.lcatextbook.com/

Sustainability Frameworks

The following review attempts to clarify prevailing confusion about the sustainability of materials consumed worldwide. The frameworks included are: Lean Thinking (lean), Pollution Prevention (P2), Zero Waste (ZW), Circular Economy (CE), and Sustainable Materials Management (SMM). Each of these frameworks is concerned with the flow of materials in the economy in some form, and is included for its emphasis on materials and/or wastes in the industrial context.

Of these five frameworks, Lean Thinking and Zero Waste are wholly concerned with waste reduction, albeit the definition of waste is broader in the lean framework. Pollution Prevention emphasizes the reduction and/or elimination of substances of concern – chemicals that affect environmental and/or human health adversely. Circular Economy emphasizes economic growth with greater material efficiency. Sustainable Materials Management focuses on the quantification and reduction of environmental burdens associated with material consumption in the economy. These two concepts have much overlap, yet differ in implementation priorities due to often competing priorities of economic growth for circular economy and environmental stewardship for sustainable materials management. Their philosophical differences necessarily lead to different priorities, approaches, and outcomes.

This review examines both the theoretical framework advocated by the leading proponent(s), as well as the most common version of the framework as currently implemented. In addition, each framework is overlaid onto a generic material life cycle as a means to normalize the discussion and highlight gaps in the theory and practice of each framework.

It is worth noting that there exists opportunities within these frameworks to influence social parameters, but these are often overlooked. The social equity or wellbeing opportunities are often not realized because the foci are limited to material efficiency and economic value generation. An outcome of such singular focus on either environmental or economic aspects of development activities is that competing agendas are often promoted under the sustainability banner leading to confusion in priorities among their intended stakeholders, particularly those people whose work might be touched by the focus areas of multiple frameworks. This confusion is widespread among diverse stakeholders, resulting in muddled decision-making or policy priorities, making it difficult to measure, track progress and communicate. In addition, material efficiency and economic value consistently rewards lowest cost per unit, a relative impact reduction approach, thus introducing complex scenarios whereby socially relevant issues are overlooked.

Lean Thinking

Lean Thinking[13] encompasses a wide range of practices that focus on efficiency and elimination of waste in all its forms. Although *lean* is not a sustainability framework per se, the practices therein are typically applied to systematically minimize waste within a manufacturing system without sacrificing productivity or quality. *Lean* also takes into account waste created through operational overhead inefficiencies and waste created through unevenness in workflows. "The

[13] Henceforth referred simply as "*lean*."

core idea is to maximize customer value while minimizing waste. Simply, *lean* means creating more value for customers with fewer resources. *Lean* applies in every business and every process. It is not a tactic or a cost reduction program, but a way of thinking and acting for an entire organization" (Lean Enterprise Institute, 2017). As such, lean is well-aligned with many aspects of materials sustainability frameworks including Zero Waste, Sustainable Materials Management and Circular Economy. Each of them, for their part, is concerned with waste minimization or elimination, responsible materials management, and process efficiency across the manufacturing and distribution chains. *Lean* does not address social disparities that may arise due to the optimization of industrial processes leading to automation and job displacement.

Lean manufacturing has a long history for industrial optimization and continuous process improvement with early adoption by Henry Ford and more contemporary adaptions by another automaker, Toyota (Lean Enterprise Institute, 2017a). The continuous improvement concept is captured in the Japanese word *Kaizen*, representing a long-term approach to work that systematically seeks to achieve small, incremental changes in processes in order to improve efficiency and quality in the long run.

Core Principles of Lean Thinking

The five-step thought process for guiding the implementation of Lean Thinking techniques described by the Lean Enterprise Institute is depicted in Figure 7. It starts with understanding the purpose or customer problems being solved, followed by a focus on the process of evaluating the value of each step in the process making sure that all the steps are linked by process flow. Finally, there is an emphasis on people and the roles needed to continually evaluate that value stream in terms of business purpose and *lean* process, all with a critical eye towards efficiency, streamlining and waste elimination.

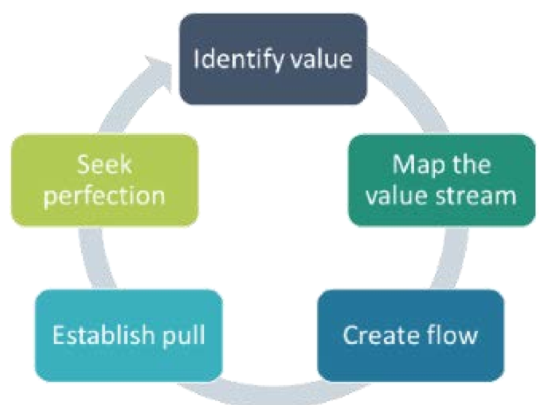


Figure 7 Principles of Lean Thinking

The five-step thought process for guiding the implementation of *lean* techniques is easy to remember, but not always easy to achieve (Lean Enterprise Institute, 2017b):

- Specify value from the standpoint of the end customer by product family.
- Identify all the steps in the value stream for each product family, eliminating whenever possible those steps that do not create value.
- Make the value-creating steps occur in tight sequence so the product will flow smoothly toward the customer.
- As the process flow is introduced, let customers pull value from the next upstream activity.
- As value is specified, value streams are identified, wasted steps are removed, and flow and pull are introduced, begin the process again and continue it until a state of perfection is reached in which perfect value is created with no waste.

The term ‘value’ from *lean* directly speaks to efficiency and waste elimination. The industrialist Henry Ford said "... while picking up and recovering scrap is a public service, designing so that there will be no scrap is an even higher public service." When the same thinking is superimposed onto the sustainability dialogue of solid waste reduction – for both generation and disposal – the language of Lean Thinking and the language of materials management begin to coalesce, and the outcomes sought begin to illuminate the mutual goals. Process efficiency and the removal of waste in all their forms that epitomizes the Lean Thinking school of thought can be effectively quantified in the LCA approach to represent the principles of eco-efficiency and environmental impact reduction. The waste hierarchy in Figure 5 can be seen as a specific form of Lean Thinking in the solid waste management space. Here the upper tiers of prevention (reduce) and rescue (reuse) can be seen as efficiency improvement measures that can be effectively assessed by LCA to represent the potential for any associated environmental impact reduction.

Lean Thinking and Material Life Cycle

The *lean* emphasis on material and process efficiency has a significant overlap with the environmental stewardship agenda of waste prevention, recovery and disposal strategies. The synergy between Lean Thinking and the environmental burdens associated with wastes is described by Verrier et al (2016) and is illustrated in Figure 8. The illustration identifies wastes in the form of overproduction, defects, excess inventory, unnecessary processing, motion, transportation and waiting time. Most of these wastes of material, processing, and/or time can easily be translated into indicators that represent environmental burdens associated with those parameters. They include rubbish or solid waste, excessive use of resources, energy, and water, direct emissions, and health and safety implications. Several *lean* wastes can also be tied to direct and/or indirect human welfare and social indicators in the forms of diminished worker health and safety, and diminished human life potential. An earlier version of this

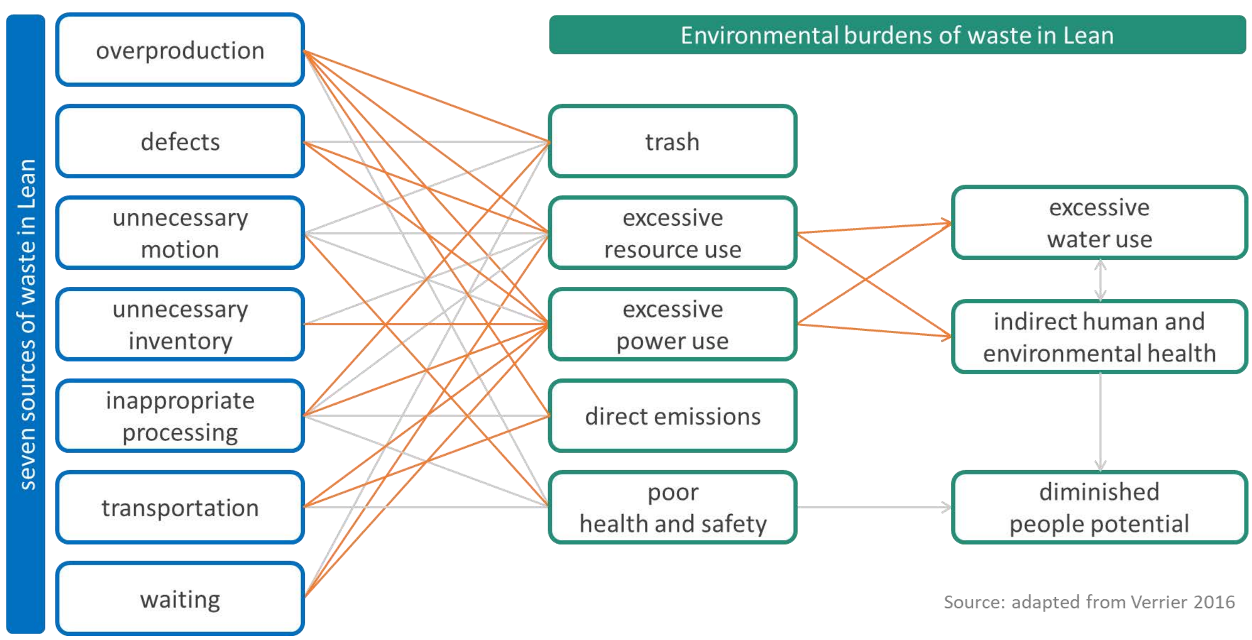


Figure 8 Link between Lean Thinking and environmental burdens of wastes

synergistic framework was reported by U.S. Environmental Protection Agency in 2007 in the Lean and Environmental Toolkit.[14]

Figure 8 shows how the priorities of *lean* to remove wastes addresses various environmental burdens throughout the life cycle of materials shown in Figure 6. The material life cycle, therefore, provides a handy apparatus to view where *lean* practices operate – both in principle and in practice. Such a perspective can help to illustrate common ground, gaps or omissions, and opportunities to collaborate with practitioners of other frameworks described herein. Lean Thinking as a practice area has been implemented in manufacturing and operations worldwide for decades, and has evolved into specialized industry-specific applications. Figure 9 shows the preceding *lean* perspective across the full life cycle of materials. Each blue circle indicates the

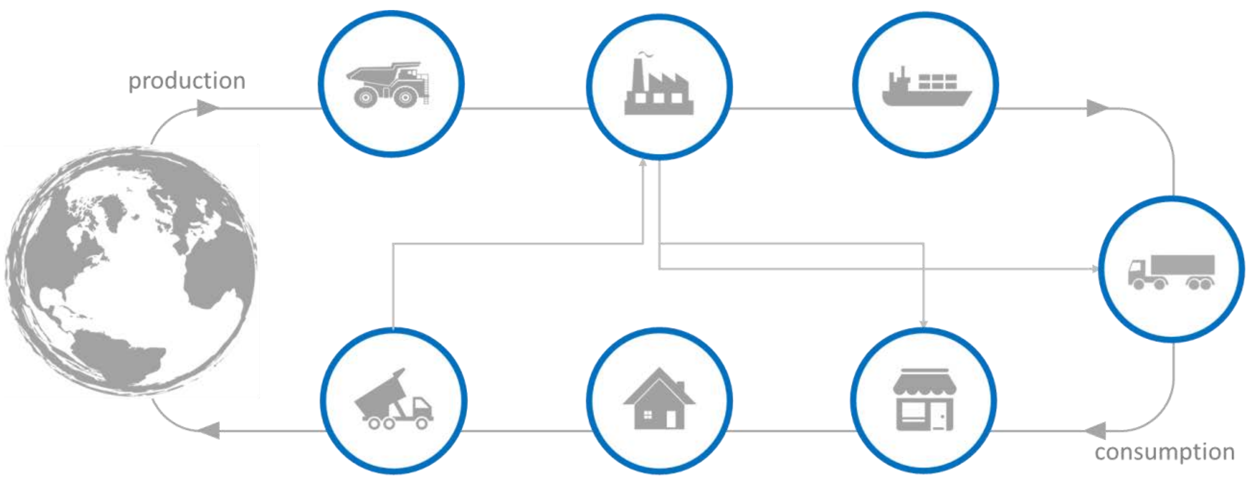


Figure 9 Theoretical and practical application of Lean Thinking in the material life cycle

(Solid circles at a life cycle phase depicts that *Lean* can be and is functional within the life cycle stage.)

life cycle stage where Lean Thinking is theoretically of significant utility. As seen in the illustration, all life cycle stages have the potential to gain material efficiencies via elimination of wasteful steps. Lean Thinking, therefore, is theoretically applicable throughout the material and product life cycles. Significant practical application of *lean* is evident for all the life cycle stages as depicted in Figure 9 making *lean* a well-established industrial framework that dovetails with aspects of sustainability frameworks that focus on efficiency and waste reduction.

It is important to recognize that *lean* is not a sustainability framework since impact assessment is not part of its practices. We suggest here that its practices are amenable to various material related sustainability agenda. While *lean* is efficient at removing wastes, its inherent focus on value creation (economic) can lead to making efficiency-based choices that could lead to significant unintended consequences when viewed from an environmental and human exposure/health perspective.

[14] For further exploration of the EPA Lean Toolkit see: https://www.epa.gov/lean/lean-environment-toolkit-content-acknowledgments

Pollution Prevention

Pollution Prevention (P2) is any practice that reduces, eliminates, or prevents pollution at its source. Pollution Prevention as a materials sustainability framework is most commonly used to describe efforts that focus on toxic or hazardous substances. Pollution Prevention is also known as "source reduction" and is the ounce-of-prevention approach to waste management. Reducing the amount of pollution produced means less waste to control, treat, or dispose of. Less pollution means less hazards posed to public health and the environment (U.S. EPA, 2017). The premise of reduction via prevention is an embodiment of the waste hierarchy of Figure 5, and is entirely consistent with the leading ecological and systems thinking concerning human and ecological health burdens related to industrial activities. The P2 hierarchy, Figure 10, slightly modifies the basic waste management hierarchy of Figure 5 to accommodate the end of pipe nature of the many pollution releases to the different media – air, water and land.

Although environmental pollution is typically the domain of regulatory compliance dealing with end of pipe discharges and emissions, P2 offers a flexible framework to engage and implement actions that reduce the use of substances of concern, improve processes to reduce discharge and emissions, seek out alternatives to the status quo operations, and work within the forward thinking "beyond compliance" mindset.

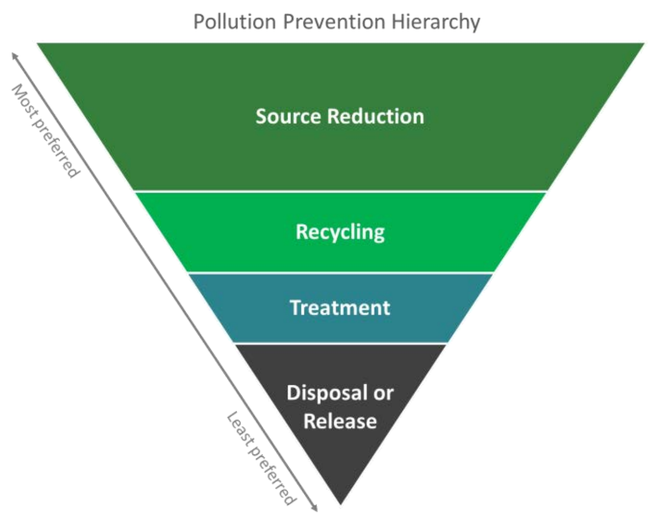


Figure 10 Pollution Prevention hierarchy

Pollution Prevention approaches can be applied to all potential and actual pollution-generating activities in all industrial sectors. Prevention practices are essential for preserving wetlands, groundwater sources and other critical ecosystems – areas in which we especially want to stop pollution before it begins (U.S. EPA, 2017). The term includes: equipment or technology modifications; process or procedure modifications; reformulation or redesign of products; substitution of raw materials; and improvements in housekeeping, maintenance, training or inventory control (U.S. EPA, 2017a).

Core Principles of P2

The mandate of P2 is straightforward – prevent pollution in all its forms from occurring to avoid all the associated burdens – ecological and human health risks, regulatory costs, remediation costs, diminished productivity and diminished systems resiliency. Pollution Prevention is not just the responsibility of businesses and government agencies – residents can help solve environmental problems by reducing pollution at the source, before it is created.

Pollution Prevention is a significant materials sustainability framework because it operates in all three dimensions of sustainable development by:

- Protecting the environment by conserving and protecting natural resources.
- Reducing both financial costs (waste management and cleanup) and environmental costs (health problems and environmental damage); both cost categories are often borne by society.
- Provides for more efficient use of financial resources through more efficient production in industry and less need for households, businesses and communities to handle waste.

Pollution Prevention and Material Life Cycle

Because pollution can occur throughout the life cycle of materials and products, opportunities for avoidance of emissions and discharges of concern are afforded to each stage of the material flow from raw substance extracting to processing and manufacturing, distributing, using and discarding. Figure 12 depicts how P2 lends itself to be functionally applicable and useful at all stages of the life cycle of materials. As alluded to earlier, concerted efforts to control pollution along the material life cycle can manifest in regulatory compliance that sets thresholds for

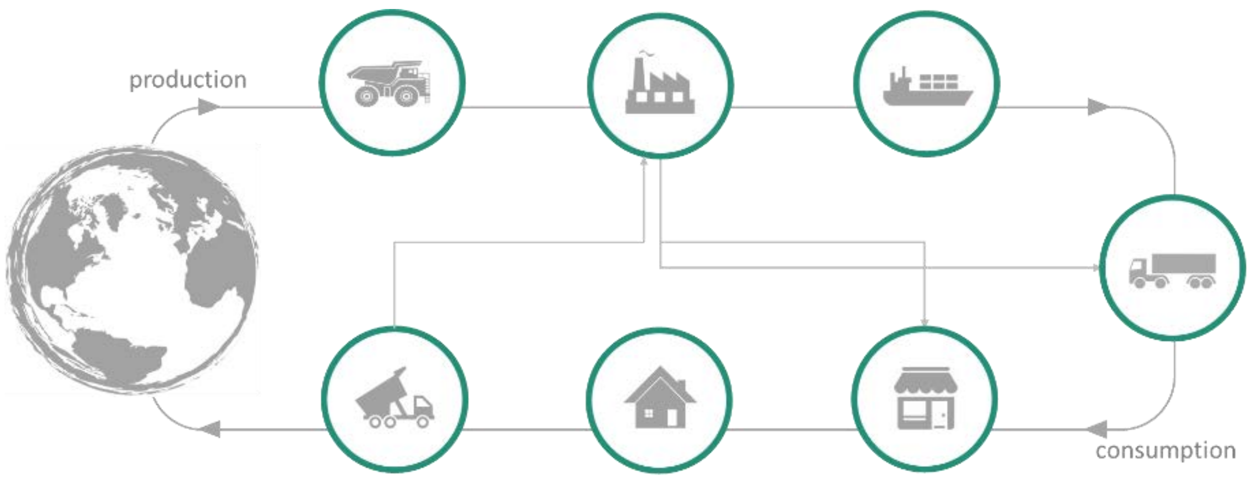


Figure 11 Theoretical application of Pollution Prevention practices in material life cycle

(Solid circles at a life cycle phase depicts that P2 can be fully operational within the life cycle stage.)

emission controls. While P2 can originate from the compliance lens, the concept of “beyond compliance” seeks to transition away from basic regulation-based emissions control to more proactive, voluntary and forward looking approaches that incorporate leading thinking about source control and product design – both formulated and assembled items – to eliminate pollutants before entering the environment.

This forward looking framework has in its toolkit such tools as process audits, life cycle assessment, green chemistry[15], and alternatives assessments[16].

- Life cycle assessment helps to identify hotspots or areas within the life cycle of materials and products where disproportionate environmental and human health impacts occur, to evaluate material and design choices and options, set baseline and track progress and more. LCA is generally well suited for evaluating macro materials or those used for their structural properties such as plastics, textiles or concrete, and for processing those materials.
- Green chemistry has P2 as a foundational principle: it "prevents pollution at the molecular level" (U.S. EPA, 2017b). Green chemistry is the design of chemical products and processes that reduce and/or eliminate the use or generation of hazardous substances. This approach requires an open and interdisciplinary view of material and product design, applying the core principle that it is better to consider waste and hazard prevention options during the design and development phase, rather than disposing, treating and handling waste and hazardous chemicals after a process or material has been developed (Beyond Benign, 2017). For a technology to be considered consistent with principles of Green Chemistry, it must accomplish three things (Warner Babcock, 2017):
    1. It must be more environmentally benign than existing alternatives.
    2. It must be more economically viable than existing alternatives.
    3. It must be functionally equivalent to or outperform existing alternatives.

Pollution Prevention as a sustainability framework offers great potential for sustainable development both in theory and in practice. The practical application of P2 is represented in Figure 12 and shows that transportation phases with their somewhat common end of pipe emissions control offer limited holistic P2 focus at present. Electrification of the transport infrastructure and modes may shift that in the future, and hence they are denoted using dotted circles. This represents a small difference between theoretical applicability (Figure 11) and practical implementation of the framework shown in Figure 12. As an overall view, however, P2 is a well-established framework, with P2 laws on the books in many states. Its applicability throughout the material life cycle makes P2 a good entry point into further and deeper sustainability efforts.

[15] Green chemistry is the design of chemical products and processes that reduce or eliminate the generation of hazardous substances. To learn more see: https://www.beyondbenign.org/about-green-chemistry/ and https://www.epa.gov/greenchemistry

[16] A chemical substitution or alternatives assessment framework is an arrangement of analyses and decisions that can be used to assess alternatives to chemicals of concern. A number of approaches exist. For details see: http://www.oecdsaatoolbox.org/Home/AAGuides

Figure 12 Current practical implementation of Pollution Prevention in the material life cycle

(Solid circles at a life cycle phase depicts that P2 is fully operational within the life cycle stage. Dotted circle suggests that P2 is marginally operational within that life cycle stage.)

Pollution Prevention like other sustainability frameworks relies on the earnest participation of the producing industries and the consuming communities to realize its potential. As mentioned earlier, many laws exist that create a framework of compliance for pollution of all types. For the beyond compliance approaches to truly be scaled, P2 activities often need stimuli or incentives from the various sectors of the economy. Unfortunately, P2 is often limited by a lack of readily available information about the pollutants, much of which is protected under the veil of intellectual property or trade secrets laws. Yet, P2 remains an upstream alternative to end-of-pipe regulations. Its potential to avoid pollution via preemptive process evaluation is a significant opportunity for material stewardship writ large. Producing industries have a significant role in facilitating material transparency to live up to various sustainability claims proffered. Many government entities across the country offer technical assistance to businesses to help navigate both the compliance driven actions and to help identify opportunities for specific sectors to prevent pollution at the source.[17]

Zero Waste

The Zero Waste doctrine asserts that “it is possible to totally eliminate the artificial, social construct of garbage,” and that “redesigning everything so that discard never takes place is much better than creating huge piles of discards and then ineffectually trying to capture a few scraps of value” (Zero Waste Institute, 2017). In theory, *zero waste* includes recycling but goes beyond recycling by taking a whole system approach to the vast flow of resources and waste through human society. It maximizes recycling, minimizes waste, reduces consumption and ensures that products are made to be reused, repaired or recycled back into nature or the marketplace (GrassRoots Recycling Network, 2017). This whole systems vision underpinning

[17] As an example, explore Pollution Prevention efforts and technical support offered by Oregon DEQ: http://www.oregon.gov/deq/Hazards-and-Cleanup/ToxicReduction/Pages/Pollution-Prevention.aspx

zero waste thinking lends itself to the sustainability agenda, and supports both the economic and ecological dimensions directly while also reducing the burdens to society as described.

Core Principles of Zero Waste

The Zero Waste Business Principles establish the commitment of companies to achieve *zero waste* and further establish criteria by which workers, investors, customers, suppliers, policymakers and the public can assess the resource efficiency of companies. They include (Zero Waste International Alliance, 2006):

1. Commitment to the triple bottom line[18]
2. Use Precautionary Principle[19]
3. No waste to landfill or incineration
4. Responsibility: takeback products and packaging
5. Buy reused, recycled and compostable
6. Prevent pollution and reduce waste
7. Highest and best use
8. Use economic incentives for customers, workers and suppliers
9. Products or services sold are not wasteful or toxic
10. Use non-toxic production, reuse and recycling processes

The Zero Waste International Alliance states that "Zero waste means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them. Implementing Zero waste will eliminate all discharges to land, water or air that are a threat to planetary, human, animal or plant health" (Zero Waste International Alliance, 2009).

Regrettably, this definition fails to mediate between competing objectives: eliminating the volume of waste, eliminating the toxicity of waste, conserving all resources, recovering all resources, and not burning or burying them. For example, the logic of no waste to landfill requires that all materials be designed as recyclable or compostable in order to avoid burning or burying them. Yet, studying product and package systems via life cycle assessments has shown many instances where recyclable (and recycled) or compostable (and composted) materials[20]

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[18] The phrase "the triple bottom line" was first coined in 1994 by John Elkington, the founder of a British consultancy called SustainAbility. His argument was that companies should be preparing three different (and quite separate) bottom lines. One is the traditional measure of corporate profit—the "bottom line" of the profit and loss account. The second is the bottom line of a company's "people account"—a measure in some shape or form of how socially responsible an organization has been throughout its operations. The third is the bottom line of the company's "planet" account—a measure of how environmentally responsible it has been. The triple bottom line thus consists of three Ps: profit, people and planet. It aims to measure the financial, social and environmental performance of the corporation over a period of time (The Economist, 2009).

[19] When human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm. Morally unacceptable harm refers to harm to humans or the environment that is: a) threatening to human life or health, or; b) serious and effectively irreversible, or; c) inequitable to present or future generations, or; d) imposed without adequate consideration of the human rights of those affected (World Commission on the Ethics of Scientific Knowledge and Technology (COMSET), 2005).

[20] Note: Recyclable and compostable are design or purchasing criteria and attributes specified by brands, institutional buyers, and the public. Recyclability and compostability are aspirational attributes, meaning that they hold the potential for recycling or composting at the end of its useful life. The package may or may not be actually recycled or composted. Even if it is, the act of recycling or composting does not obviate all of the impacts of production.

do not consistently result in net environmental benefit, suggesting that at times managed disposal might still result in the lowest net environmental impacts, and a necessary end-of-life treatment route (Vendries, et al., 2018). The claim that "implementing *zero waste* will eliminate all discharges . . ." is also problematic. Eliminating "all discharges" is impossible according to the laws of physics, and total recycling at best reduces, but does not eliminate, the impacts of materials (U.S. EPA, 2009).[21]

Figure 13 illustrates the Zero Waste decision hierarchy taken from Zero Waste International Alliance (ZWIA). The prioritization to "promote cyclical use" above "design for sustainability" suggests a willingness to promote circularity (via recycling) over broader sustainability principles (i.e., toxics elimination, use of lower-impact materials). Cyclical use is another way of saying closed material loops, which is predicated on recycling. And, recycling does not encompass the breadth of ideas in Design for Sustainability or Design for Environment (DfE) strategies – both involve looking at the life cycle burdens associated with a product system, not just end-of-life options.

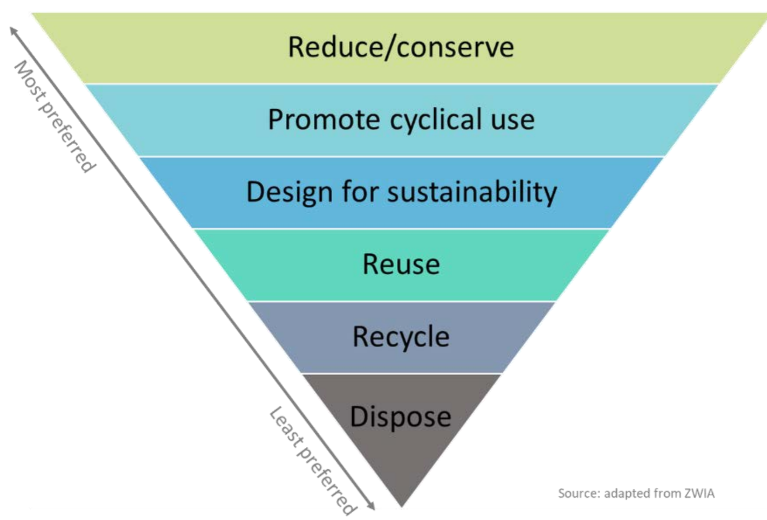

Figure 13 Zero waste hierarchy

This approach raises a fundamental question: to what "wastes" does the Zero Waste framework apply? Is it municipal solid wastes (garbage), as implied by the directive to avoid landfilling and incineration? Alternatively, is it all wastes, including but not limited to garbage, and other forms of air, water, and soil pollution? If Zero Waste primarily concerns itself with garbage, then it runs the risk of elevating "disposal avoidance" to the highest goal, and could lead to decisions that minimize solid waste disiposal while increasing environmental impacts broadly.

These internal conflicts are ingrained in common interpretations of *zero waste* and create the potential for misalignment with broader sustainability principles. For example, while the ZWIA definition could be understood to apply to either municipal solid wastes (MSW) alone, or to a much broader suite of wastes, two leading *Zero Waste* certification programs (ZWIA Zero Waste Communities and GBCI's True Zero Waste program for businesses) concern themselves primarily with municipal solid wastes. They both give credits for actions that minimize MSW with

[21] An assessment of domestic greenhouse gas emissions in the U.S .found that the production, transport and disposal of materials contributed 42 percent to the nation's emissions, and that recycling or composting 95 percent of all municipal solid waste would reduce those emissions by merely 6 percent. See https://www.epa.gov/region-9-documents/opportunities-reduce-greenhouse-gas-emissions-through-materials-and-land

only limited consideration given to broader impacts. For example, both encourage the avoidance of materials that are not compostable or recyclable, without consideration of the full environmental impacts of compostable or recyclable materials versus alternatives.

If corrected, the alignment of broader *zero waste* thinking with the preceding descriptions of Pollution Prevention and Lean Thinking could make these three actionable frameworks potential allies for process level sustainability. Together they may, and to varying degrees do support the larger goals of sustainable development within the industrial spheres where material flows originate but do not necessarily end.

Zero Waste and Material Life Cycle

The theoretical principles of Zero Waste offer a solid footing for the framework to be applied across all phases of material and product life cycle, and is illustrated in Figure 14. Other than transportation to retail, where zero waste to landfill may have lower utility, Zero Waste as a framework for sustainability has potential for the entire material life cycle.

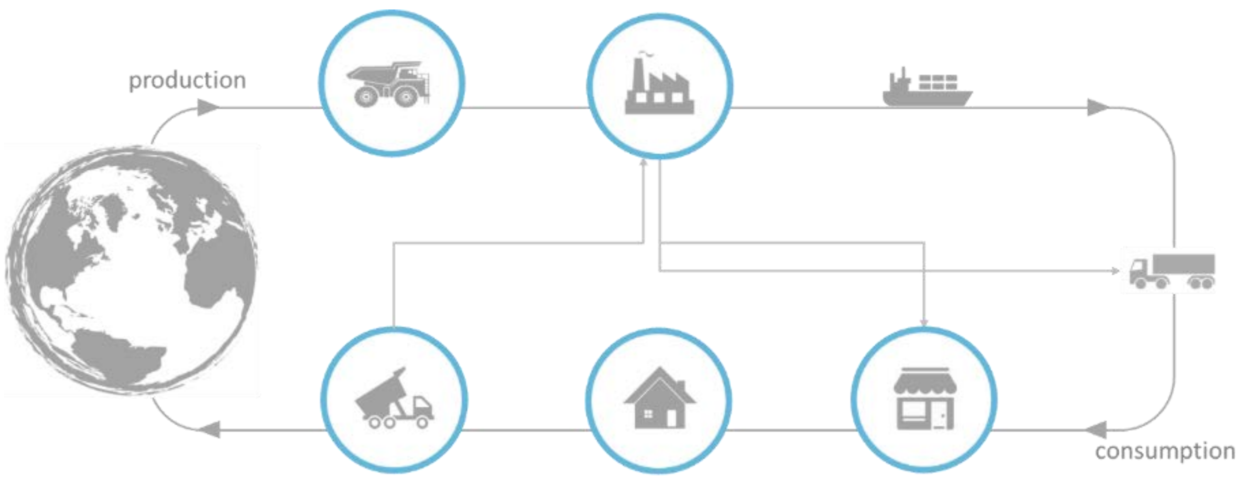

Figure 14 Theoretical application of Zero Waste practices in the material life cycle

(Solid circles at a life cycle phase depicts that Zero Waste can be fully operational within the life cycle stage.)

For zero waste to function effectively it must be applied across all phases of the material or product life cycle. Zero waste thinking has to become part of standard operating procedures akin to the earlier Lean Thinking discussion to critically identify opportunities to reduce all types of wastes upstream during concept development, production and retail distribution. While the focus is typically on end-of-life management, the bulk of life cycle impacts of products is locked in during the design steps when the materials are selected for their functional requirements. Design choices also trickle down into how the product is distributed, used and treated after its useful life. While in theory the holistic version of *zero waste* offers a framework to reduce environmental burdens, within the framework itself there is minimal measurement to prioritize the types of wastes to be removed. Tools such as LCA discussed earlier can be invaluable to better quantify environmental burdens and target high impact wastes first.

At least in the U.S., the Zero Waste movement has suffered from severe oversimplification that has relegated its broad scope to focus on end-of-life management of discards (municipal solid waste), and has limited *zero waste* to be principally concerned with recycling (or composting) and diverting materials away from landfill and other treatment routes. On the surface this may seem like a good simplification, yet recall the material hierarchy in Figure 5 which places recycling towards the lower end of waste reduction activities, well below prevention strategies and a last resort before disposal. This overly constrained interpretation of *zero waste* has diverted the attention away from its whole system vision and into a fairly limited construct. As a result, rather than focusing on all wastes and emissions, *zero waste* implementation is dedicated to solid waste only. This has resulted in companies, communities, and residents acting with good intentions to divert waste from reaching landfills, and make recycling and composting the pinnacles of materials stewardship without considering if this yields environmental benefits or makes economic sense.

Waste recovery systems come with their own contribution to the overall environmental impacts and must be factored into the equation for net environmental benefit. For example, many metal recycling facilities have caused such local contamination that they've been added to EPA's Superfund list. Similarly, the negative pollution, social and health impacts of e-waste and plastic exported to developing countries are significant and often overlooked in the accounting for recycling activities. One hundred percent recovery of different materials comes with additional burdens as each material and form exhibit a threshold or breakeven point beyond which more environmental damage is invested than being offset via recovery through recycling alone. This is particularly important when life cycle burdens are overlooked in favor of end-of-life management.

Benefit-burden quantification therefore is critically needed. Most Zero Waste programs measure their progress using a landfill diversion rate, which is a measure of the reduction in tons sent to landfill (or waste incinerator) when compared to a historic baseline. This simple measure is insensitive to the composition of materials, the means of reduction, or an acknowledgement that the environmental burdens of different materials and diversion pathways vary dramatically in their scale.

From a communications perspective, *zero waste* seems simple to communicate, but is potentially confusing and subject to interpretation, and may undermine broader sustainability considerations. Its simplicity runs the risk of elevating "landfill avoidance" to a penultimate objective in the minds of the public, potentially encouraging "wishful recycling" by introducing contamination, while also undermining the upper tiers of the waste hierarchy. Indeed, if the public or industry understands the primary objective to be "zero waste to landfill" then it might not matter how such landfill avoidance is achieved: prevention and reuse are no more important than recycling or composting, in contrast to the hierarchy shown in Figure 5. For Zero Waste to contribute at its highest potential to material sustainability practitioners must incorporate analytical approaches more common to other frameworks, and move away from a rigid 'recycling at any costs' approach.

The effect of some of these limitations is depicted in Figure 15. It shows how Zero Waste is rooted in the waste treatment and retail parts of the material or product life cycle. Zero waste efforts could better align with broader sustainability goals by shifting focus from minimizing one type of waste (MSW) to considering multiple wastes, including air and water emissions. To achieve sustainability, a systematic approach must be used to prioritize both high-impact materials and end-of-life treatment mechanisms that lower the net human health and environmental impacts. This can be achieved using existing tools such as life cycle assessment and taking learned knowledge from other more analytical frameworks discussed herein. Such a systematic approach can identify the inherent environmental burdens of materials and design. It can illustrate how some recyclable and recycled material can result in higher overall environmental burdens than functionally equivalent materials that aren't recyclable or recycled.

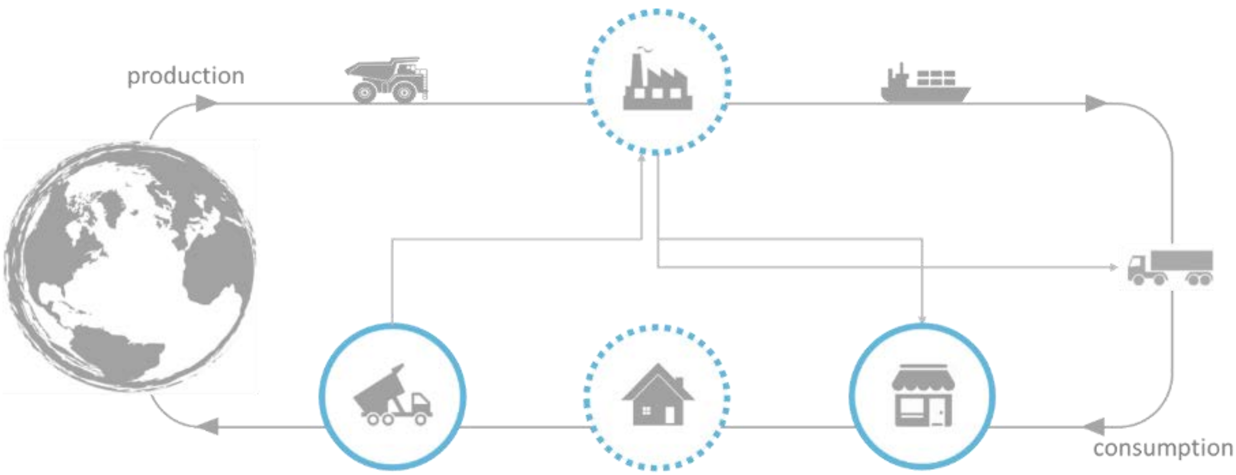

Figure 15 Current practical implementation of Zero Waste in material life cycle

(Solid circles at a life cycle phase depicts that Zero Waste is fully operational within the life cycle stage. Dotted circle suggests that Zero Waste is marginally operational within that life cycle stage.)

A systematic approach can also help to optimize for the environment and then consider the recovery at the end of the product's useful life. Recycling is a beneficial act, but only if it produces net benefits considering the impacts across the full life cycle. More recycling by itself isn't necessarily able to reduce the environmental burdens associated with the wide variety and formats of materials consumed.

Circular Economy

The overarching theme of the Circular Economy movement is optimizing the flow of materials in the global economy by closing the material loops from production to the end of a product's useful life. "A circular economy is a regenerative system in which resource inputs, waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling" (Ellen McArthur Foundation, 2017). "It is an alternative to a traditional linear economy (take, make, use, dispose) in which resources are kept in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life" (WRAP, 2017). Circular economy offers a model that seeks to decouple economic growth from resource constraints by reducing reliance on virgin materials. At the same time, circular economy is principally concerned with economic development and supporting economic growth via a closed material loop approach. Economic growth is the primary focus; environmental and social aspects of sustainable development are considered beneficial side effects of a high-functioning economy, not a central focus in the Circular Economy framework.

The circular economy theory, as promoted by the Ellen McArthur Foundation (EMF), renews enthusiasm in the business community for strategies such as reuse, repair, refurbishment, remanufacturing, repurpose and recycling (see Figure 16). This theory and framework is well aligned with the waste hierarchy depicted in Figure 5, except for one important exception: it often excludes any reference to the most-preferred method in the hierarchy, prevention (source reduction). While a strong appeal of circular economy is in its elegant simplicity of closed loops for a resource efficient economy, the visceral elegance may be adding to confusion and generating interpretations that may not be holistic. Recent studies suggest that Circular Economy business initiatives to date predominantly focus on recycling (Bocken, Olivetti, Cullen, Potting, & Lifset, 2017).

Core Principles of Circular Economy

The Circular Economy concept is built upon an earlier concept of Cradle-to-Cradle[22] popularized by William McDonough and Michael Braungart. Cradle-to-Cradle champions a design ethos based on systems thinking and closed materials loops as an alternative to the predominantly linear take-make-use-discard material flows within industrial systems. The technical and biological cycles are elevated to an economic level and into a continuous, positive development cycle. The framework speaks to the preservation and enhancement of natural capital, optimization of resource yields, and minimization of system risks by managing finite stocks and renewable flows. Circular Economy intertwines other concepts such as performance economy, biomimicry, industrial ecology, natural capitalism, blue economy, and regenerative design. Three core principles are illustrated in Figure 16 (Ellen McArthur Foundation, 2017):

1. Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.
2. Optimize resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.
3. Foster system effectiveness by revealing designing out negative externalities.

[22] See William McDonough and Michael Braungart. Cradle to Cradle: remaking the way we make things. New York: North Point Press, 2002. Cradle-to-Cradle is also referred to in literature as C2C.

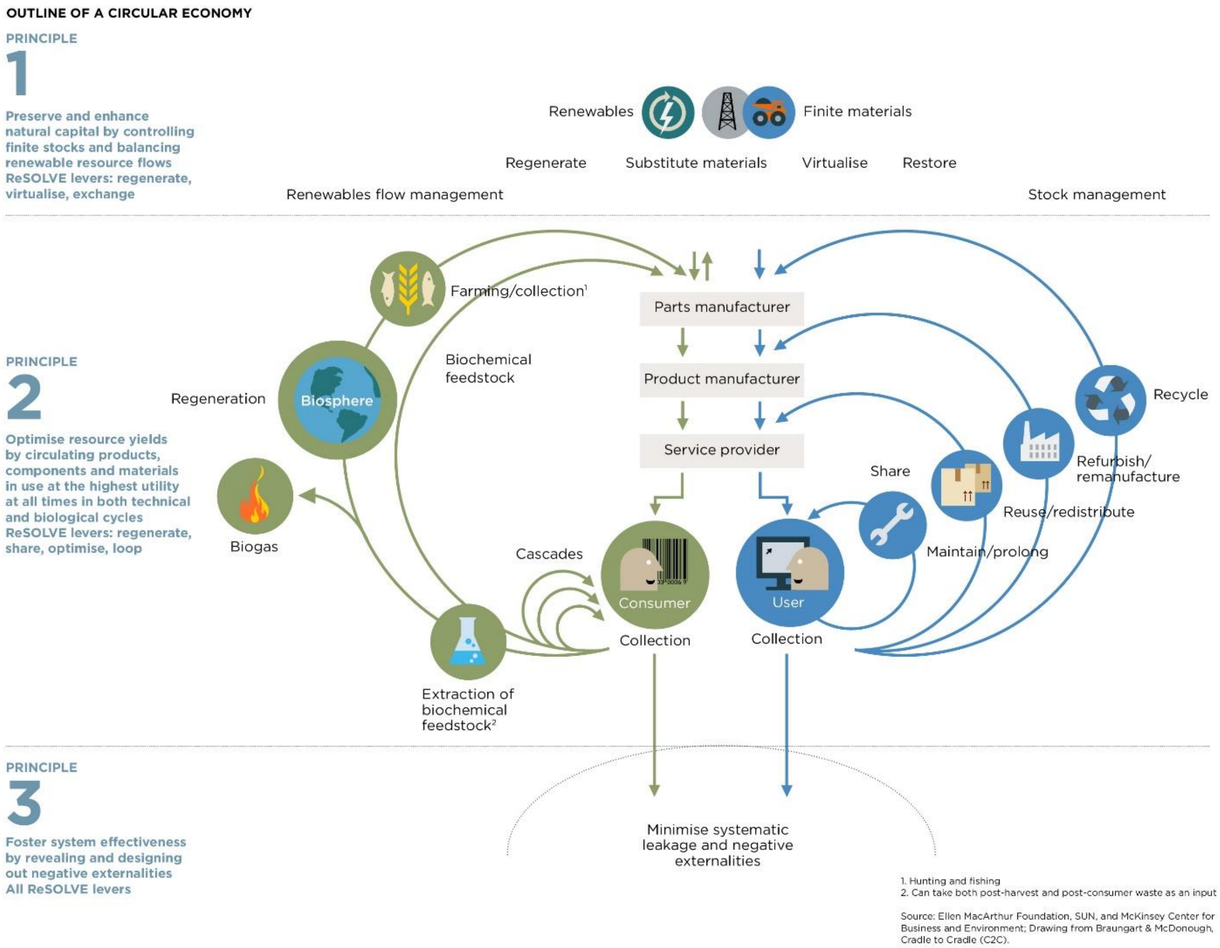

Figure 16 Outline of Circular Economy by the Ellen McArthur Foundation

Image source: https://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram

Circular Economy and Material Life Cycle

Circular economy could, in concept, operate at all stages of the life cycle of materials as depicted in Figure 17. In practice, however, circular economy may not be able to function on its own without relying on other existing frameworks to supplement its ambitious goals of redesigning the product manufacturing processes starting with changing how materials are created, used, recovered and repurposed.[23, 24] Indeed, circular economy attempts to incorporate many other concepts including biomimicry and regenerative design to reimagine the economic engine. This integrative approach could be a strong lever for change, yet at present the central focus appears to be on closing material loops. Material discussions acknowledge resource

[23] See The New Plastics Economy, https://newplasticseconomy.org/

[24] See A new textiles economy: Redesigning fashion's future https://www.ellenmacarthurfoundation.org/publications/a-new-textiles-economy-redesigning-fashions-future

depletion and scarcity, yet the dialogue is short on decreasing overall demand or reducing environmental damage. Therefore, “whether the ideas that make up the circular economy are novel or not is, in many ways, less important than ensuring that lessons from past attempts are fruitfully exploited in the current efforts. Further, CE proponents argue that it is the integration of previous strategies and concepts where the framework can and should make its greatest contribution. This prompts the question of how the Circular Economy can learn from the methods and findings of industrial ecology, and what new ideas—or combination of ideas—the circular economy is bringing to industrial ecology” (Bocken, Olivetti, Cullen, Potting, & Lifset,

Figure 17 Theoretical application of Circular Economy principles in the material life cycle

(Solid circles at a life cycle phase depicts that Circular Economy can be fully operational within the life cycle stage.)

2017).

Circular Economy is billed as a “new economic model (that) seeks to ultimately decouple global economic development from finite resource consumption” (Ellen MacArthur Foundation, 2015), thereby allowing (in theory) continued economic growth even as absolute environmental impacts increase. While laudable, there are several inherent limitations to this approach.

First, at a fundamental level the Circular Economy framework introduces critical disconnects from the laws of thermodynamics that govern materials at the atomic level. The second law of thermodynamics stipulates that the total entropy (disorder) of an isolated system always increases over time. The entropic increases are always present in material processing, attributed to mixing, downgrading and down-cycling processes (Cullen, 2017).

Infinite looping of existing material stocks without infusion of virgin inputs is problematic. Some materials degrade with each use cycle, others may have numerous alternate routes for secondary uses, and yet other materials have relatively poor recovery pathways worldwide. For example, paper fibers deteriorate over three to five recycling cycles depending on use, requiring input of new tree-based fibers. Metals, though in theory are infinitely recyclable, have many competing uses in industry with varying life spans of the metal-containing products. In a growing global marketplace recovered metals get absorbed into many alternate pathways, thus requiring fresh virgin production to meet the growing demand. Plastics as a class of materials offer an astonishing array of functional properties resulting in a menagerie of resin types that are used in combinations or modified with additives to achieve the desired performance. This front-end flexibility of plastics development result in a complex flow of products rendering the end-of-life stewardship and management of this extraordinarily complex material class problematic and expensive.

Additionally, decoupling – in this case reducing the environmental burdens per unit of production – doesn’t square with the Circular Economy principles to preserve and enhance natural capital and foster system effectiveness if it is accompanied by an increase in consumption (i.e., economic growth). The benefits of such “relative" decoupling are typically obviated by increases in overall production and consumption. "Half the impact with double the sales" translates into no reduction in environmental impacts at all, so long as "half the impact" is expressed on a relative basis (half the impact per unit of production). Missing from many discussions of circular economy strategies for businesses is an acknowledgment of the primacy of science-based environmental limits, or an acknowledgment that business operates on a finite planet, (see Figure 4), with finite resource flows and a finite ability to absorb wastes. Because perpetual circular systems are only theoretical and can only be achieved by breaking laws of physics and nature, a continuous growth approach is also not possible. This means that economic growth and increasing consumption as a means to enhanced wellbeing as underlying principles must be questioned in both the linear and circular economy. A circular economy may be preferable to a linear one, but could still be deeply unsustainable.

Circular Economy’s ideal of closed material loops must also contend with the inherent hazards of substances used throughout the material life cycle. Infinite looping of toxic substances is problematic and diminishes the value of a closed material economy. Here, circular economy could promote a “benign by design” approach more vigorously. The concept is central to an emerging Green Chemistry design ethos that champions chemical design for function without inherent hazards. In a recently published paper by the Ellen McArthur Foundation, Michael Werner, chemist at Google states: “If we are going to keep materials flowing in commerce longer, we have to design them to be safe for human and environmental systems, because we can’t change the chemistry of products once we put them out in the world.” The report further concludes: “The consequences of the current linear take-make-waste economic model are evident—persistent toxification, ecosystem degradation and lost economic value. Unlocking and accelerating the realization of a circular economy requires that we create safe materials and build the systems, infrastructure and technology to keep safe molecules flowing endlessly (Google and Ellen McArthur Foundation, 2018). This acknowledgment is indeed a positive development.

There are other more practical concerns with this framework. For a circular material economy to manifest as envisioned, the notions of product stewardship and extended producer responsibility will need to be widely accepted so that the burden of closing the material loops does not rest on communities as it does presently. In the current system of global material flows, producing entities largely outsource material stewardship via MSW management to communities, or into the social realm of sustainable development. The responsibility for closing the loops is relegated to community or regional waste management authorities, where the expectation is that the said community must invest in infrastructure and services to ‘’reverse engineer’’ the materials found in complex product and packaging into their base constituents for industry to reintegrate into the production flow.

Relinquishing the responsibility of end-of-life materials management to society allows industry to effectively and efficiently extract value from materials through products in terms of revenue, brand image, and other intangibles, while simultaneously externalizing the environmental burdens and end-of-life management. Much emphasis is placed on individual choice and actions. This construct is at the root of the linear take-make-use-discard material flow that circular economy proponents aim to change into closed loops. A strong starting point may be to flip this construct and demand life cycle stewardship of materials by producing and/or distributing entities.

Figure 18 reflects the on the ground rollout of circular economy based on direct dialogue, observation and critical review of scientific literature on the topic. It shows that while in principle Circular Economy is a framework with the potential to support the entire material life cycle (Figure 17), in practice, its principle avenue of engagement (at least in the U.S., where Circular Economy is a relatively new concept) is at the end of the useful life of materials. This includes using recycled materials, shifting to renewable and biobased sources, and designing for recyclability (or compostability). A strong emphasis on optimization for recovery at end of life is promote. An example is the recent circular economy pledges made by many multinational companies including Amcor, Coca-Cola, Unilever, Tetra Pak and Danone to make their product packaging 100% recyclable by 2025. The Ellen MacArthur Foundation estimates that these companies together influence more than six million metric tons of plastic packaging each year (Inside Waste, 2018).

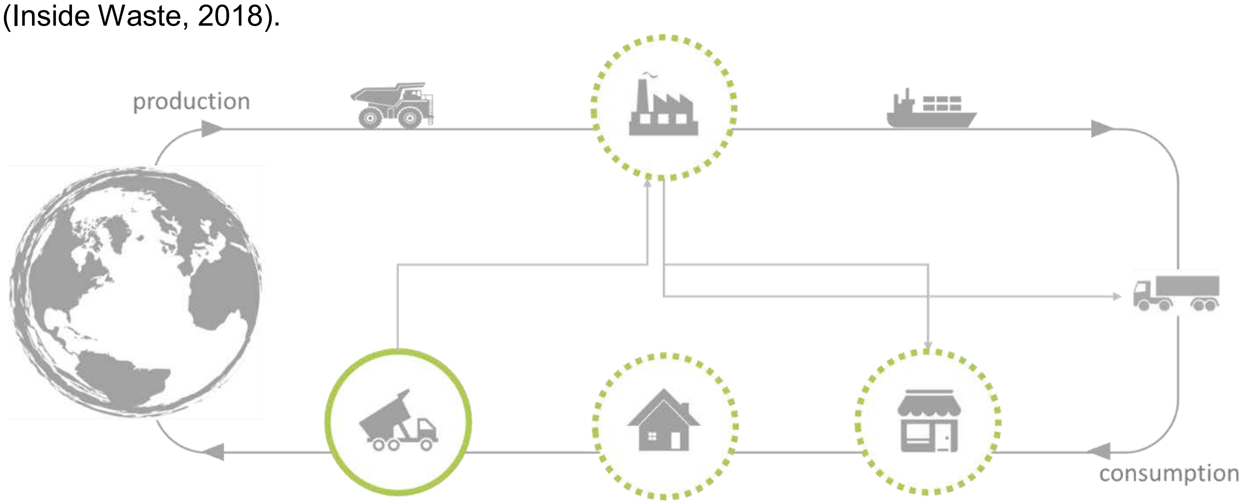

Figure 18 Current practical implementation of Circular Economy in the material life cycle

(Solid circles at a life cycle phase depicts that Circular Economy is fully operational within the life cycle stage. Dotted circle suggests that Circular Economy is marginally operational within that life cycle stage.)

Such pledges on the surface appear to be a positive move in an environmental sense, but without considering the life cycle impacts of different alternatives it is difficult to predict the net outcomes based simply on attributes such as recyclability or compostability (Vendries, et al., 2018). In addition, the pledge does not appear to prioritize recovery based on the impacts of materials, packaging formats, the volume of material involved, or tradeoffs. A wholesale recyclability clause treats packaging designs, material throughput, product durability and other important parameters as irrelevant to the discussion or being equally important. Without considering these other variables, packaging formats that use less materials and may have low impact but are not recyclable are considered less favorable, while packaging that might be recyclable but carry much higher environmental burdens is favored. That may not be the intent of the pledges, yet such may be the result.

Industrial production and retail distribution are two stages where circular economy appears to be growing traction as an increasing number of global brands have signed on to the Circular Economy agenda, and significant thought is put into increasing efficiencies of pre-consumer or industrial off-spec materials.[25] This is indeed a positive sign as circular economy has the potential to influence diverse supply networks across the planet. With momentum growing around this framework, important questions about its potential weaknesses must be addressed in earnest either internally or via cooperative and collaborative engagements. “Now that the concept of the Circular Economy has gained traction across varied domains, critical questions emerge. When do circular economy practices lead to net environmental benefits? Under what social, economic, or political conditions are circular strategies likely to succeed? If viable strategies are identified, how should they be scaled? How can we engender significant structural changes in the way we use resources and move beyond incremental improvements in rates of low-grade recycling and waste minimization? How can more advanced circular economy strategies, beyond recycling, be adopted by business?" (Bocken, Olivetti, Cullen, Potting, & Lifset, 2017). Another critical question must also be asked: How can a circular economy flourish without addressing ever-increasing consumption for a growing global human population?

Sustainable Materials Management

Sustainable Materials Management (SMM) is a systemic approach to using and reusing materials safely and more productively over their entire life cycles. It represents a change in how our society thinks about the use of natural resources and environmental protection. By looking at a product's entire life cycle, we can find new opportunities to reduce environmental impacts, conserve resources and reduce costs (U.S. EPA, 2017c). Sustainable materials management includes waste prevention as well as discard management; this latter role traditionally has been managed at the community or municipal level. It places those important activities within the wider framework of material flows in society and economic activity. More broadly, sustainable materials management identifies both impacts across the full life cycle of materials and products, and the actions to address those impacts (Figure 19). Impacts and actions are viewed across the entire life cycle (e.g., not limited to solid waste), giving sustainable materials management an explicitly broad scope. This life cycle includes extracting raw materials, manufacturing, transporting, consuming, using, reusing, recycling and disposing (Oregon DEQ, 2012).

[25] See Ellen McArthur Foundation. Case Studies. https://www.ellenmacarthurfoundation.org/case-studies

Figure 19 Material life cycle supporting Sustainable Materials Management (U.S. EPA)

The Organization for Economic Cooperation and Development (OECD) has been developing and promulgating international policies aimed at preventing and reducing waste generation and managing the residues in an environmentally sound manner since the 1980s. The OECD concluded that it has become evident that waste minimization policies that address only end of life of products and materials are not effective in reducing the increasing amounts of waste associated with economic activity and material consumption. This accentuates the need for creative, far-sighted and integrated solutions, using life cycle thinking to reduce the negative environmental impacts of materials. Sustainable materials management offers an integrated solution to address current environmental concerns linked to material consumption (OECD, 2017). To some extent, Sustainable Materials Management is an alternative to – or even in response to – the more narrowly-defined frameworks such as Zero Waste that appear to be primarily concerned with one life cycle stage (end of life) or one type of environmental impact (solid waste).

Sustainable materials management is principally concerned with understanding and improving the environmental outcomes of industrial and societal activities relating to the consumption of materials (UNEP, 2010). Materials are broadly defined and include things that are important for their structural properties (e.g., paper, plastics, metals, concrete, etc.), functional properties (e.g., chemicals) and those that are important as energy carriers to humans (e.g., food) and machines (e.g., fuels). Because sustainable materials management takes a broad perspective to managing environmental burdens of material consumption, it is entirely feasible to include the social and economic realms within the considerations of sustainable materials management as they relate to environmental stewardship and resource conservation. Emerging methods for life cycle assessment are grappling with the social indicators[26] associated with material extraction, outsourced production, manufacturing and end-of-life management. In depth environmental footprinting of economic activity is a well-developed practice.[27]

Sustainable materials management is grounded in life cycle thinking and uses the systematic approach for the responsible use and management of all material related activities – for both macro and micro materials. This means there is an inherent affinity towards measurement, data analysis, and science-based targets. A significant body of research exists under the Industrial

[26] A social life cycle assessment (S-LCA) is a method that can be used to assess the social and sociological aspects of products, their actual and potential positive as well as negative impacts along the life cycle. This looks at the extraction and processing of raw materials, manufacturing, distribution, use, reuse, maintenance, recycling and final disposal. See https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/social-lca/

[27] For an example, see Consumption-based Greenhouse Gas Emissions Inventory for Oregon https://www.oregon.gov/deq/mm/Pages/Consumption-based-GHG.aspx

Ecology banner that includes multidisciplinary concepts such as cleaner production, life cycle assessment, material flow analysis, biomimicry, Design for Environment, process engineering, impact assessment, hazard and risk assessment, pollution prevention and more. All this valuable research focused on specific industrial activities is leveraged within the sustainable materials management framework to optimize the materials life cycle from virgin resource acquisition to finished material, to component and product, to waste product, and to ultimate disposal (Garner & Keoleian, 1995).

Sustainable materials management is both a contributor to and a user of this rich repository of scientific inquiry into the industrial systems and materials flows. This aspect of SMM is an opportunity for other frameworks to leverage as applicable to raise the bar on their respective actions. For example, research that illuminates the life cycle impacts of specific materials, products, industrial systems, cities or communities, etcetera, can be used by proponents of Lean Thinking, Zero Waste, Circular Economy, and Pollution Prevention to make informed decisions to advance their specific agendas while staying true to the underlying sustainability goals. The other frameworks can also apply a systems approach to evaluate possible new initiatives.

Core Principles of Sustainable Materials Management

Sustainable materials management is currently the only framework that accounts for impacts and management of materials across systems and at every point in the material life cycle. By doing so, sustainable materials management also sets into motion a methodological shift for quantifying environmental and human health burdens based on prevailing science. Science-based targets for critical environmental impacts consider the global condition and the inherent carrying capacity of the planet to establish clear and measurable limits to work from. Using this approach can offer businesses, cities, regions and countries a way of setting goals that are rooted in the reality of global changes to the biotic and abiotic systems of the planet, and goals that can be consistently tracked for progress.[28] Ideally, sustainable materials management policies ensure that materials provide needed functions in a way that conserves resources, reduces waste, slows climate change, and minimizes the environmental impacts of the materials consumed across the communities where they are produced, used, and discarded, ultimately bringing both resource and pollution levels below acceptable limits as defined quantitatively and scientifically. These practices also aim to be economically efficient and include less easily monetized community benefits, such as societal impacts[29] and improved quality of life (U.S. EPA, 2015).

[28] For a detailed example of a climate change management program based in current science see: Science Based Targets http://sciencebasedtargets.org

[29] The inclusion of social aspects of material consumption is a nascent endeavor. In LCA the release of the Social Hotspot Database has opened up the possibility to include basic labor and other implication related to communities where production takes place. For details see Social Hotspot Database at https://www.socialhotspot.org/.

The OECD definition of sustainable materials management embodies four main principles (OECD, 2012):

- Preserve natural capital;
- Design and manage materials, products, and processes for safety and sustainability from a life cycle perspective;
- Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental, and social outcomes; and
- Engage all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes

Balancing the multiple objectives of sustainable materials management can be difficult and confusing. Full implementation of this approach requires a broad understanding of the critical interactions of material flows through the economy, society, and the environment; often these flows involve global movements of resources that are difficult to track and measure. Changes often rely on decentralized adjustments in the behavior of individuals [and corporations]. At both a national and a community level, common sustainable materials management strategies and objectives have centered on the following goals (Fiksel, 2006; U.S. EPA, 2015):

- Decrease urban demand for material consumption
- Decrease resource intensity of products & services
- Use substitute materials with lower life cycle impact
- Encourage local sourcing of materials & products
- Increase recycling rates for commodity materials
- Recover and reuse wasted or underutilized resources
- Assure proper disposal for unwanted solid wastes
- Create economic incentives for material efficiency

The sustainable materials management strategies best aligned to achieve these goals typically encompass a suite of integrated practices (e.g., green design, take-back strategies, recycling, managed disposal, and others) working in tandem to reduce overall environmental impacts. These goals emerge from careful interactions between leadership and broad stakeholders that are supported by high-quality data and a range of economic and environmental analyses. Sustainable materials management aims to provide a holistic view and manage materials across different sectors of society. This may require long-term thinking about both the impacts of human behavior, and the most effective ways to improve it (U.S. EPA, 2015).

The material flow and policy loop supporting sustainable materials management is depicted in Figure 20 and shows the interplay between ecological systems where resources are extracted, and where they are used in industrial systems to fulfill demand from human societies. The material feedback loop of the three realms of sustainable development is, in theory, maintained via an appropriate combination of policy instruments and voluntary actions by all actors. By default, sustainable materials management applies quantitative tools such as life cycle assessment, green chemistry principles, risk assessment, material flow analysis among others, and qualitative frameworks that rely on stakeholder engagement, interviews and indices that measure social interaction and human health. By relying on multiple tools, sustainable materials management can offer insights about the environmental and human health implications of choices made in industry or society to inform appropriate actions and policy approaches. It further allows practitioners to prioritize actions based on the magnitude of environmental burdens imposed by using different materials in different product categories. Of course, all these techniques are equally available to other frameworks discussed herein, yet are not typically central to their philosophy due limited focus on economic and/or solid waste aspects.

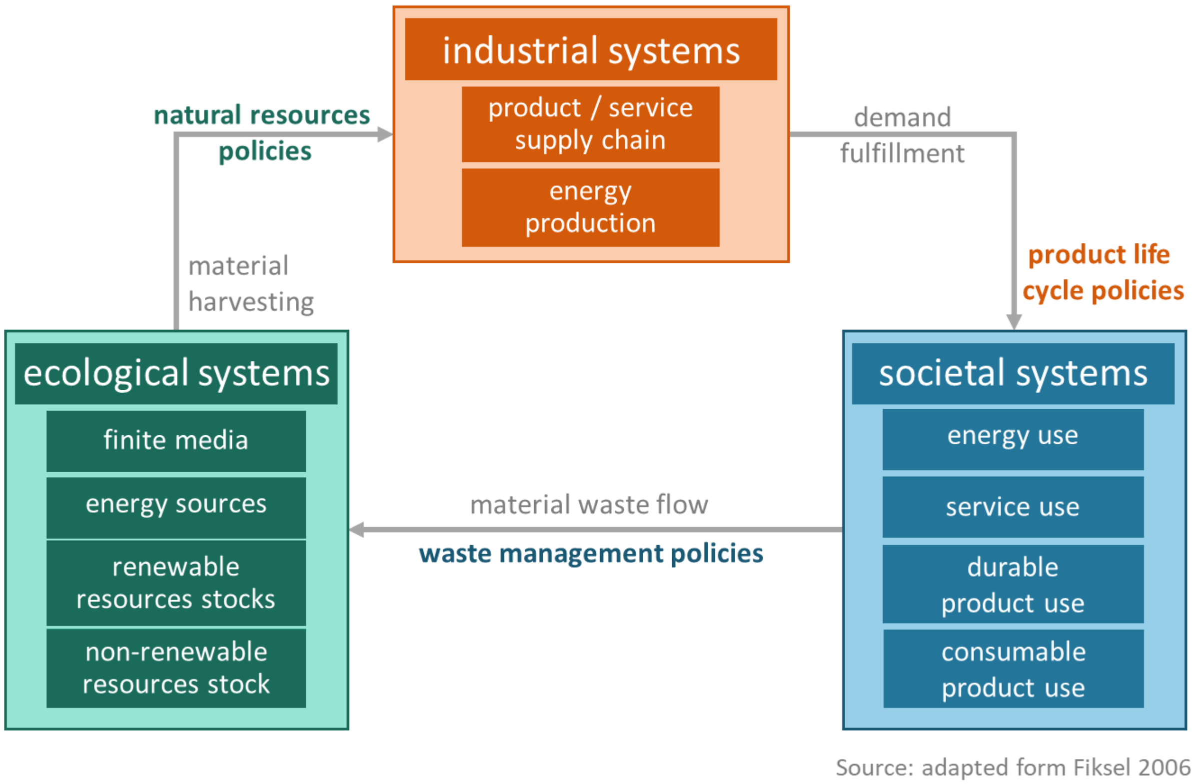

Figure 20 Material and policy loop supporting Sustainable Materials Management

Sustainable Materials Management and Material Life Cycle

As with most of the other sustainability frameworks discussed in this review, sustainable materials management is well suited to operate at all phases of the material life cycle as depicted in Figure 6. The whole system approach at the root of sustainable materials management offers a systematic lens to focus attention on specifics within each life cycle stage to identify hotspots – areas with disproportionate burdens in relation to the whole material or product life cycle – and devise actions to remediate impacts or eliminate them via appropriate design practices. In contrast, frameworks such as Zero Waste and Circular Economy have focused the upstream design criteria to meet a set of narrowly defined outcomes at end of useful life. For example, Zero Waste and Circular Economy advocates often call for all packaging to be recyclable or compostable, without consideration of full environmental impacts, as opposed to optimizing for the full life cycle of the materials involved.

By focusing on broader environmental impacts, and not exclusively on municipal solid waste disposal metrics, sustainable materials management aims to support policies and decisions that have clear benefits for reducing environmental burdens that matter to human well-being: toxics, greenhouse gas emissions, water withdrawals and the like, as opposed to the weight of materials in landfills. While Figure 22 illustrates the theoretical suitability of sustainable materials management to the full material life cycle, in practice sustainable materials management has not reached its full potential as shown in Figure 21. The focus is currently skewed toward solid waste management, with some emerging traction in production, distribution network and household stages of the material life cycle. Here entities such as the Oregon DEQ[30] is forging ahead by incorporating life cycle thinking in a variety of efforts.[31]

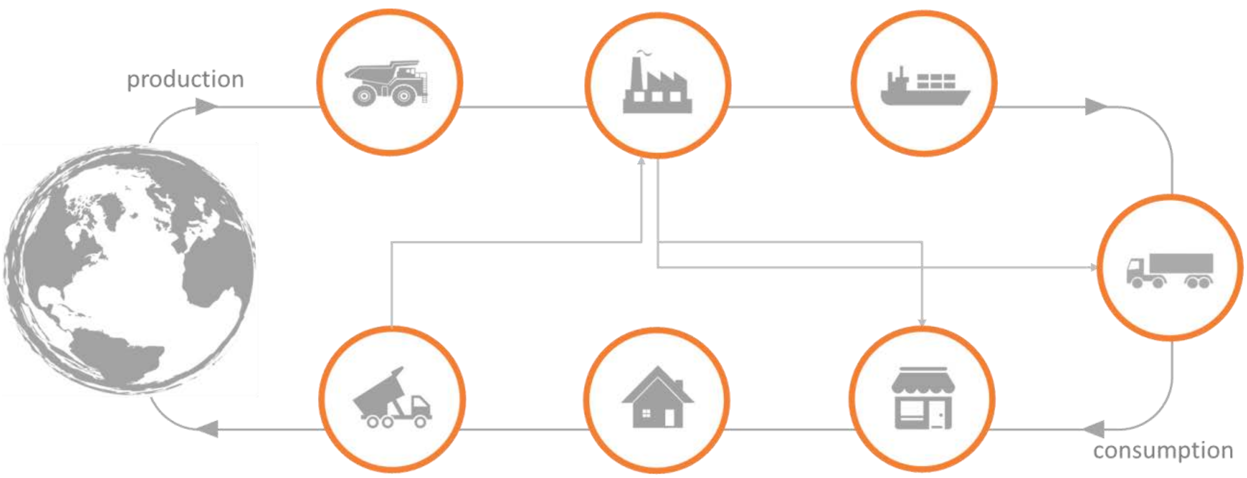

Figure 22 Theoretical application of SMM in the material life cycle

(Solid circles at a life cycle phase depicts that Sustainable Materials Management can be fully operational within the life cycle stage.)

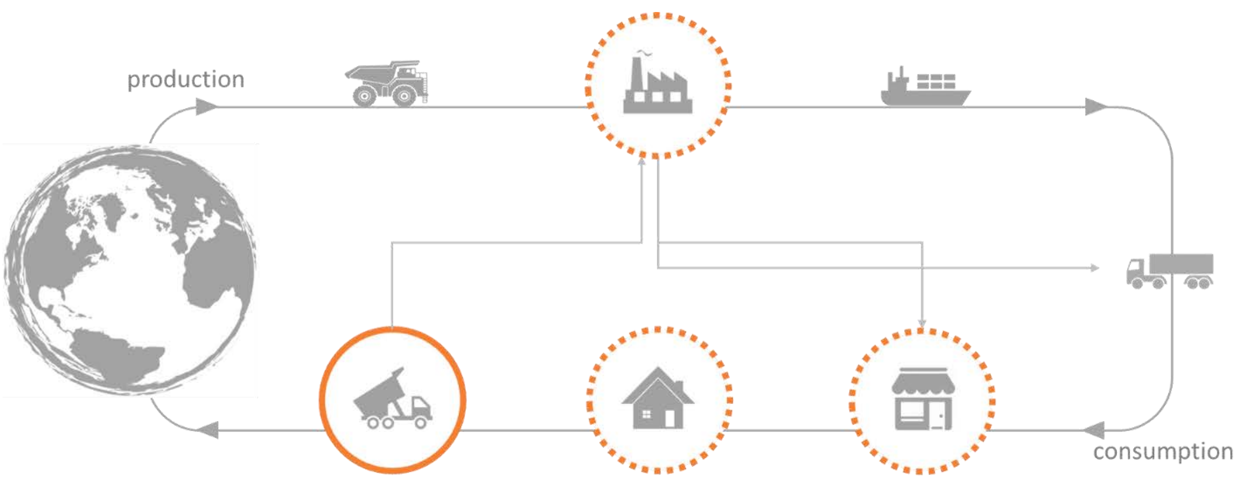

Figure 21 Current implementation of SMM principles in the material life cycle

(Solid circles at a life cycle phase depicts that Sustainable Materials Management is fully operational within the life cycle stage. Dotted circle suggests that Sustainable Materials Management is marginally operational within that life cycle stage.

[30] See What is Materials Management https://www.oregon.gov/deq/mm/Pages/What-is-Materials-Management.aspx

[31] See Production and Design https://www.oregon.gov/deq/mm/production/Pages/default.aspx

Materials Life Cycle and Sustainability Frameworks

The life cycle lens has been useful to illustrate the focus areas of each sustainability framework – both in theory and in practice. Figures 23 and 24 illustrate the sum of the theoretical and practical activities for various frameworks discussed here. Again, these illustrations are not intended to represent with full accuracy or precision the current state of material sustainability efforts, but rather to visualize the gaps between theory and current practice, and to highlight the life cycle stages for areas of collaboration. Looking through the theoretical lens, Figure 24, one could easily conclude that sustainability as a global effort is robust and should yield the desired outcomes of ecological stewardship, with a high-functioning global economy that provides for human wellbeing.

Looking through the theoretical lens one could easily conclude that sustainability as a global effort is robust and should yield the desired outcomes of ecological stewardship, with a high-functioning global economy that provides for human wellbeing. Yet, in practice significant gaps are apparent resulting in sporadic and marginal environmental or social improvement.

However, Figure 24 paints a different picture (albeit subjectively drawn). It illustrates that, individually and collectively, the sustainability efforts of different frameworks, for the most part, are focused on the tail end of the life cycle of materials – at the post-use recovery and discard of materials. This suggests that practitioners of many of these frameworks have potential to improve their impact by expanding scope of their efforts and reach into upstream stages of the materials life cycle. The purpose of reaching upstream, however, should be to achieve broader social and environmental goals such as those contained in the Sustainable Development Goals, as opposed to working upstream for the primary purpose of optimizing downstream or end-of-life solutions. Given differences within frameworks, this will clearly be easier for some than others.

This highly concentrated focus on the end-of-life part of the life cycle of materials has conflated the importance of material recovery in the popular story about consumption. The emphasis on recovery and recycling overstates the importance of managing environmental impacts at the end of life, and discounts the potential for far greater potential further upstream in the material life cycle, i.e. from production through retail delivery. The storyline has also created a self-reinforcing agenda along the product supply chain from producers, to distributors and retailers, to institutional buyers, and individual consumers. The entire system has been skewed to the narrowest potential for change and environmental stewardship. In addition, the near exclusive emphasis on recycling may have enabled a culture of “environmental guilt-free” consumption with a narrative that goes something like “as long as something is recycled or closed loop the consumption level doesn’t matter”.

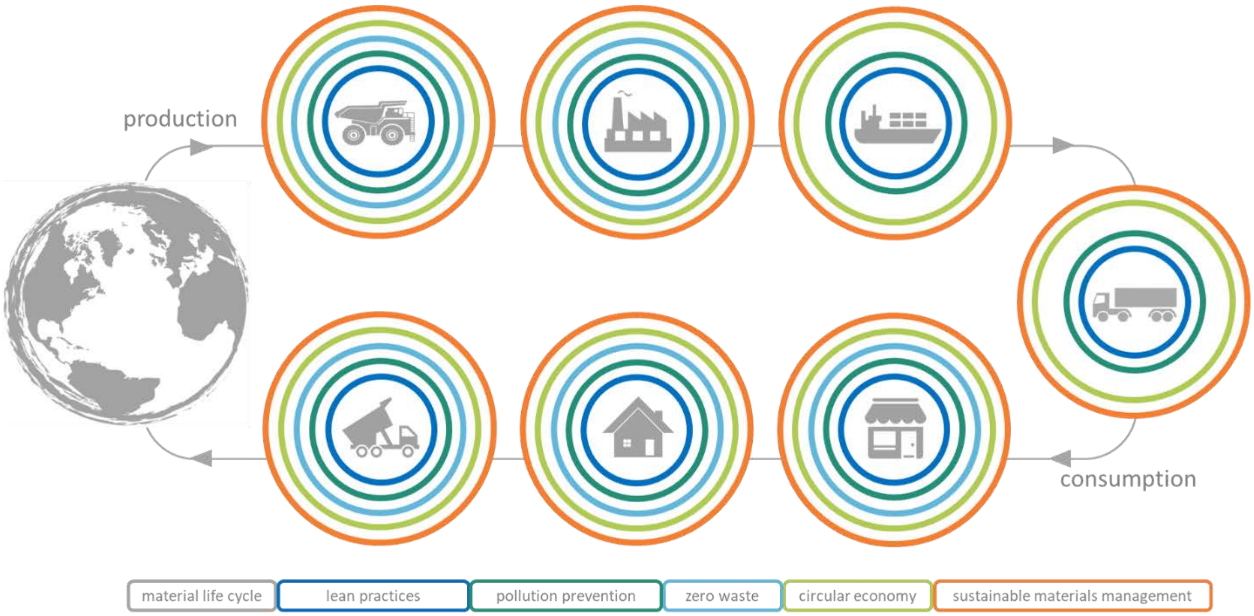

Figure 24 Sum of theoretical activities by all sustainability frameworks described

(Solid circles at a life cycle phase depicts that a given sustainability framework can be fully operational within the life cycle stage. The size of each circle is not important.)

Figure 24 Sum of practical activities by all sustainability frameworks described

(Solid circles at a life cycle phase depicts that a given sustainability framework is fully operational within the life cycle stage. Dotted circle suggests that a given sustainability framework is marginally operational within that life cycle stage. The size of each circle is not important.)

Evidence in industrial ecology literature strongly suggests that the life cycle impacts of materials from extraction to manufacture, distribution and use far outweigh the impacts of end-of-life discard management. These impacts are not offset by basic end-of-life management of materials such as recycling, composting, and energy recovery via incineration or other avenues[32]. This point seems difficult for many to fully grasp or accept. Figure 24 represents significant opportunities to reduce environmental burdens along those very parts of the supply chain since focus in those more "upstream" phases of the materials life cycle is sparse and sporadic. Opportunities exist both through traditional efficiency-based approaches (reduction of impacts per unit of production), as well as design considerations that optimize material use, reuse, and recovery. It also includes new cultural and business models that leverage approaches that shift from material consumption to service utilization with closed material loops where they make sense, and more.

A Collaborative Approach to Material Sustainability

A key intent of this paper is to promote cooperative, synergistic and more collaborative approaches to material sustainability that benefit the three dimensions of sustainable development – environment, society and economic enterprises. As a central theme, careful and considered whole system materials stewardship can offer opportunities for reduced environmental burdens and positively affect long-term resilience of the systems that provide, make, use and recover materials. This premise hinges on many factors including the integration and coordination of activities generally undertaken by practitioners of various sustainability frameworks, collectively working to lower the various environmental burdens that come with material consumption.

There is a growing body of scientific and anecdotal evidence that highlights the reality that narrowly targeted activities promoting incremental improvements with a "less bad" philosophy is insufficient to make the systems-level shifts needed for long term resilience. Within the material and product life cycle depicted in Figure 6 much focus is on the end-of-life recovery of materials for recycling, composting, and in some cases, energy recovery via incineration. Although end-of-life activities are an essential part of material sustainability, by themselves they are insufficient for several reasons.

First and foremost, because resource extraction through production is typically the most intensive and impactful steps of most product life cycles[33]. Second, because there is a great deal of systems inefficiency resulting in high levels of leakage or losses from material extraction to when a product is delivered to the final user. End-of-life treatment of materials does nothing to affect those inefficiencies.[34] Third, supporting a continuous growth model of economic

[32] For example see a comparison of bottled and tap water using life cycle analysis, http://www.oregon.gov/deq/mm/Pages/Drinking-Water.aspx

[33] For examples, see Environmental Footprints of Foods https://www.oregon.gov/deq/mm/food/Pages/Product-Category-Level-Footprints.aspx

[34] As an example, see Alexander, Peter et. al. 2017. Losses, inefficiencies and waste in the global food system. Agricultural Systems 153 (2017) 190–200.

development is limited by real planetary boundaries.[35] The Earth cannot provide the material resources demanded by economic activity, and more critically, cannot absorb the entropic releases to air, water and soil in the form of pollution, wastes, and ecosystem damage and destruction. Ever-increasing consumption cannot be the path forward as planetary resilience is steadily destabilized. In the same vein, competition among various sustainability frameworks cannot be the path forward for environmental stewardship at scale.

At present however, the sustainability frameworks reviewed in this paper are working independently with narrow agendas, and at times at odds in both philosophy and approach with the larger scope of sustainable development. To contribute more wholly to the deeper goal of improving the environmental footprint of material consumption it is incumbent upon the practitioners of the various sustainability frameworks to choose actions based on science, data, and analysis even if the findings contradict long-held assumptions. As the preceding reviews illustrate, no single framework has achieved its full potential across the life cycle of materials. Therein lies opportunities for practitioners of various approaches to learn and share toward the common goal of environmental stewardship that not only meets today's material demands, but also creates pathways that strengthen the resilience of the whole system to meet the needs of the future generations.

Ever-increasing consumption cannot be the path forward as planetary resilience is steadily destabilized. In the same vein, competition among various sustainability frameworks cannot be the path forward for environmental stewardship at scale.

Currently, Lean Thinking is concerned with process and output efficiency. Zero Waste is busy with waste diversion from landfill, recycling, and to a lesser degree, reducing waste generation as routes to sustainability. Pollution Prevention is largely driven by regulatory obligations aimed at curbing emissions. At the same time, Circular Economy has garnered a strong following for closing material loops via improved recovery and design efforts, but is not consistent in considering actual environmental impacts. Sustainable Materials Management is attempting to free society from its legacy focus of solid waste management, and systematically seeing opportunities further up the design and production cycle to affect the whole life cycle of products. Each of these frameworks is, for the most part, functioning in knowledge silos whereby limited cross-pollination of ideas occurs. Worst, at times there appears to be significant infighting and protectionism among long term practitioners with deeply held beliefs and practices. These realities can be shifted through cooperation and collaboration to advance the common ground of environmental stewardship, long term resilience of the natural systems, and economic viability.

[35] See Stockholm Resilience Center. The nine planetary boundaries. http://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

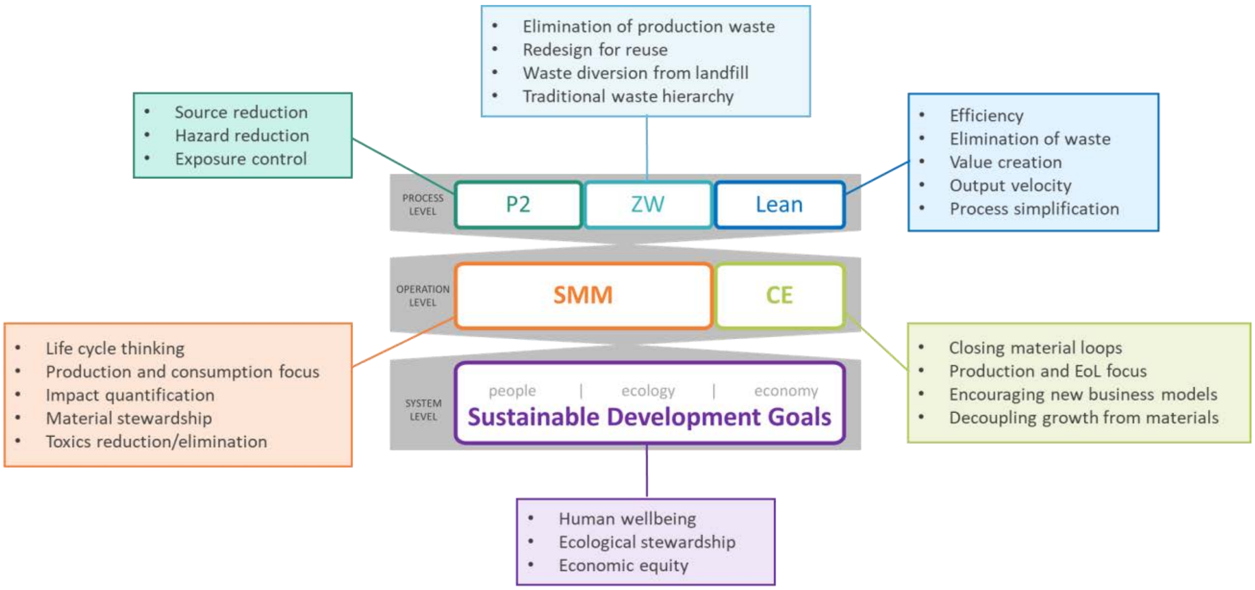

Figure 25 SDGs and priority areas of different sustainability frameworks

(P2: Pollution Prevention, ZW: Zero Waste, SMM: Sustainable Materials Management, CE: Circular Economy)

Figure 25 attempts to illustrate how different material sustainability efforts might fit together to support the larger agenda articulated in the Sustainable Development Goals. This is presented as one vision of possible integration across philosophies and practice areas. It is not intended to be a one-dimensional overlay to force-fit actions or practices, nor a suggestion that an overarching integrating philosophy needs to be developed. Rather, Figure 25 suggests that there is more in common among these frameworks that can unite and strengthen the sustainability movement than there are perceived differences. The efficiency approach of Lean Thinking and Zero Waste combined with the prevention approach of Pollution Prevention can serve as best practices for larger frameworks such as Circular Economy and Sustainable materials management. Both Circular Economy and Sustainable Materials Management can in turn support the material aspects of human development and long term resilience agenda of the Sustainable Development Goals.

Principles for Material Sustainability

- Framework ideologies must remain malleable to prevailing scientific evidence rather than established norms.
- Materials life cycles are complex and opportunities for environmental improvements can often be identified applying a life cycle approach.
- Materials should be considered and evaluated across the entire life cycle, and actions to reduce the negative impacts of materials should likewise be considered across the full life cycle.
- Recovery of material is only one part of the life cycle of materials. Optimization must occur at all stages, not just at the end of useful life of a product.
- Policymakers, government staff, businesses, nongovernmental organizations and individuals should become more familiar with the reality and magnitude of science-based environmental limits, including limits to continued economic growth absent absolute decoupling.
- Attention needs to be given to social, economic and environmental realms.

Conclusion

Materials sustainability has historically been addressed within the economic realm with efforts focusing on efficiency of use and processing, and reducing or eliminating waste. Economic development cannot, however, be separated from planetary boundaries and human wellbeing – the environmental and social dimensions. Sustainability frameworks too should not be partitioned into preferential views without considering the whole system as all actions are interlinked, particularly those pertaining to global commerce.

From Lean Thinking to Zero Waste, to Pollution Prevention, Circular Economy and Sustainable Materials Management the path to material sustainability starts with efficiency and elimination of waste and pollution, but that is just the beginning. Sustainable development and a sustainable material future will need each actor in the sustainability space to participate at their highest potential, utilizing the best tools available to reach mutual goals. It will require some give and take, learning and leading, pushing and pulling between and among actors and advocates of various schools of thought. Knowledge silos across different schools of thought are inevitable as the frameworks reviewed evolved along different professional and temporal trajectories, yet today, there is more in common between them than typically acknowledged (See Table 3). This is a strength and an asset, for the *fierce urgency of the now* is bearing down upon business as usual for material consumption. The time is *now* to act in concert for the betterment of ecological outcomes. The path forward is to reach across the knowledge silos through cooperation, collaboration and sharing. Note the significant crossover in core principles across the frameworks below. There too is room for modification of core principles to include global material realities including the social dimensions, particularly for primary extractive and producing regions and communities.

Table 3 Alignment of core principles across different frameworks

Sustainability Framework	Core Principles	P2	ZW	CE	SMM	Lean
Pollution Prevention (P2)	Protecting the environment by conserving and protecting natural resources.					
	Reducing both financial costs (waste management and cleanup) and environmental costs (health problems and environmental damage)					
	Provides for more efficient use of financial resources through more efficient production in industry and less need for households, businesses and communities to handle waste.					
Zero Waste (ZW)	Commitment to the triple bottom line					
	Use Precautionary Principle					
	Zero waste to landfill or incineration					
	Responsibility: takeback products and packaging					
	Buy reused, recycled and compostable					
	Prevent pollution and reduce waste					
	Highest and best use					
	Use economic incentives for customers, workers and suppliers					
	Products or services sold are not wasteful or toxic					
	Use non-toxic production, reuse and recycling processes					
Circular Economy (CE)	Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.					
	Optimize resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles.					
	Foster system effectiveness by revealing and designing out negative externalities					
Sustainable Materials Management (SMM)	Preserve natural capital;					
	Design and manage materials, products, and processes for safety and sustainability from a life cycle perspective;					
	Use the full diversity of policy instruments to stimulate and reinforce sustainable economic, environmental, and social outcomes;					
	Engage all parts of society to take active, ethically-based responsibility for achieving sustainable outcomes					

The stakes are high enough that cooperation and collaboration are not just nice to have, but imperatives for the path forward. Each framework described herein offers considerable insight and strengths to complete the material sustainability puzzle (see Figure 25). Together, they offer a stronger path ahead than any single framework on its own. As these multiple pathways to materials sustainability continue to evolve, the following principles may provide a unified approach to their implementation:

The 21st century is constrained by and will continue to be defined by planetary boundaries on many fronts. We must contend with climate change, degradation of productive soils, contamination of potable waters, and the collapse of ecosystems. Myriad limitations including chemical loading of soils, water and air, and species decline will impose very real restrictions on unfettered commerce. We are also encumbered by declines in social systems, culture, and the wisdom borne out of long held traditions. Sustainable development must balance the needs of all both for today and for the unrealized future. Materials sustainability is critical for this sustainable future and requires that collaboration and cooperation among the various sustainability frameworks be an imperative for the remainder of this century. No framework is an island. Some opportunities include:

- Circular Economy can be supported by Lean, Zero Waste and *pollution prevention* tactics. Circular economy must also look at the big picture, incorporate evidence and analyses amassed over decades of industrial ecological activities into their strategic plans, and consider the future of growth- and consumption-based economic models.
- Sustainable Materials Management can learn and leverage the *circular economy* panache for communicating with enthusiasm the potential for wide scale change.
- Zero Waste can benefit enormously by setting priorities based on environmental footprint analyses more common to sustainable materials management. It can also focus attention on high impact efforts, and broaden their scope from managing municipal solid wastes alone to reducing multiple wastes across the full life cycle of materials.
- Lean Thinking practitioners can incorporate environmental implications into their robust structured waste elimination framework.
- Pollution Prevention offers a fundamental groundwork to support all the frameworks discussed here.

We cannot afford to limit ourselves to narrowly contrived material stewardship tactics such as recycling or composting which represent a minor sliver of most material life cycle burdens. Instead, we need to look at the full life cycle of materials, and how they fit into the broader picture of sustainable development.

Sustainable development and a sustainable material future will need each actor in the sustainability space to participate at their highest potential, utilizing the best tools available to reach mutual goals of environmental stewardship.

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