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Review

Towards Materials Sustainability through Materials Stewardship

Christopher D. Taylor *, Benjamin Gully, Andrea N. Sánchez, Edward Rode and Arun S. Agarwal

DNV GL, Dublin, OH 43017, USA; Benjamin.Gully@dnvgl.com (B.G.); Andrea.Sanchez@dnvgl.com (A.N.S.); Edward.Rode@dnvgl.com (E.R.); Arun.Agarwal@dnvgl.com (A.S.A.)

* Correspondence: Christopher.Taylor@dnvgl.com; Tel.: +1-614-787-8995

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Abstract: Materials sustainability requires a concerted change in philosophy across the entire materials lifecycle, orienting around the theme of materials stewardship. In this paper, we address the opportunities for improved materials conservation through dematerialization, durability, design for second life, and diversion of waste streams through industrial symbiosis.

Keywords: materials sustainability; dematerialization; durability; design; strategies

1. Introduction

1.1. Materials and Sustainable Development

The theme of sustainability has emerged out of the collective awareness that prosperity can only be maintained long-term by attending to the social, environmental and economic impacts of decisions made by nations, institutes, businesses and individuals. The recently adopted UN Sustainability goals reflect widespread recognition among nations, businesses and non-government organizations of the need to improve economic, social and environmental conditions across the world [1]. From the perspective of materials, scientists and engineers, sustainability—specifically materials sustainability—requires attention to the way materials are sourced, processed, manufactured into products, maintained through the product lifecycle and redirected at their end of life. Materials sustainability is intrinsic to the broader view of sustainability—corporate, national or individual—since the processes that sustain industrialized society are dependent upon the ability to provide materials that enable prodigious levels of energy, healthcare and food generation and distribution. Whereas materials sustainability viewed as an entirely closed loop may seem unrealistic, akin to the invention of a perpetual motion machine, the progressive refinement of materials lifecycles to reduce waste and streamline processes in terms of energy and natural resource usage (including water and mined deposits) can move human societies closer to that ideal.

1.2. Motivations

Two recent books highlight popular trends with regards to materials sustainability: Extracted by Ugo Bardi [2], which updates the Limits to Growth argument and posits that "peak materials" may be looming in the 21st century for a multitude of technologically critical elements, and The Making of the Modern World by Vaclav Smil [3], a more nuanced approach that avoids extreme points of view but also acknowledges the challenges faced by a global society seeking long-term and equitable prosperity alongside environmental harmony. Whereas projections based on geological survey data and historical rates of production may suggest that some materials may be in an "endangered status" while others have a longer term (centuries) supply, of potentially greater concern, as Smil points out, is the dependence of the materials lifecycle upon external inputs of energy, water and the subsidiary outputs of carbon dioxide and other environmental pollutants. These environmental factors may ultimately pose economic, social and political pressures that will limit the extremely high rates of production that the developed nations have become accustomed to.

These longer term perspectives are not the only arguments for considering materials sustainability. Economic benefits directly emerge by attending to the issue of responsible and ethical use of materials. As an example, consider research efforts into capturing economic value out of the "red mud" discarded as a waste product from the refining of bauxite into alumina [4], or the harvesting of precious metals from electronic waste [5]. Indeed, governments, consumers and businesses alike are aware of the benefits of recycling and companies and community facilities exist to coordinate the redemption of economic value to products that would otherwise be discarded as waste (e.g., aluminum, can, and glass bottle recycling). However, many products used throughout the consumer and industrial worlds continue to be discarded due to the lack of effective and economical sorting, separation or materials recycling strategies [6]. It is a business necessity that the costs of restoring a material must be less than the material's present sale value. Therefore, research should be applied to develop technologies that lower costs for materials recovery at end of life, with a priority placed on those materials that are more globally scarce, energetically intensive to produce, or have toxic impacts on the environment [7]. From the policy perspective, incentives to recycle, penalties for emissions and a balanced approach to the proper valuation of finite natural resources need to be implemented to drive the economic motivation for practices in materials sustainability.

1.3. The Stewardship Strategy

Herein, the argument is made that working towards materials sustainability as a goal, requires materials stewardship as an active strategy. Materials stewardship is an informed approach to materials management that gives particular attention to the maintenance of the material during product ownership and the "second life" of the material after its present use expires. The topic builds from the original concept of stewardship as developed by the International Council on Mining & Metals [8]. It also has ties to the notion of a circular economy, as outlined in the following section. After introducing the topic of materials stewardship, we provide four key thrust areas that can be adopted within the materials stewardship paradigm. We then summarize and make some concluding remarks as to how materials stewardship can apply within the overall context of risk management and mitigation.

2. Materials Stewardship—A Strategy for Improving Materials Sustainability

2.1. Material Lifecycles

The concept of materials stewardship is consistent with the overall picture of the circular economy: within a circular economy, materials producers and product manufacturers work with end users, communities, retailers, service providers and waste management facilities to "close loops" for products, materials and other resources by developing "ecosystems" that mimic natural cycles [9]. The traditional "linear" once-through cycle for materials, as shown in Figure 1, is then augmented by the inclusion of feedback loops, where materials and other resources can flow back "upstream" via negotiated agreements, legislated policy or community activities that help to close the loop of the materials lifecycle. Whereas key limitations of thermodynamics will prevent complete closure [10], there are certainly opportunities for significant gains to be made within that limit.

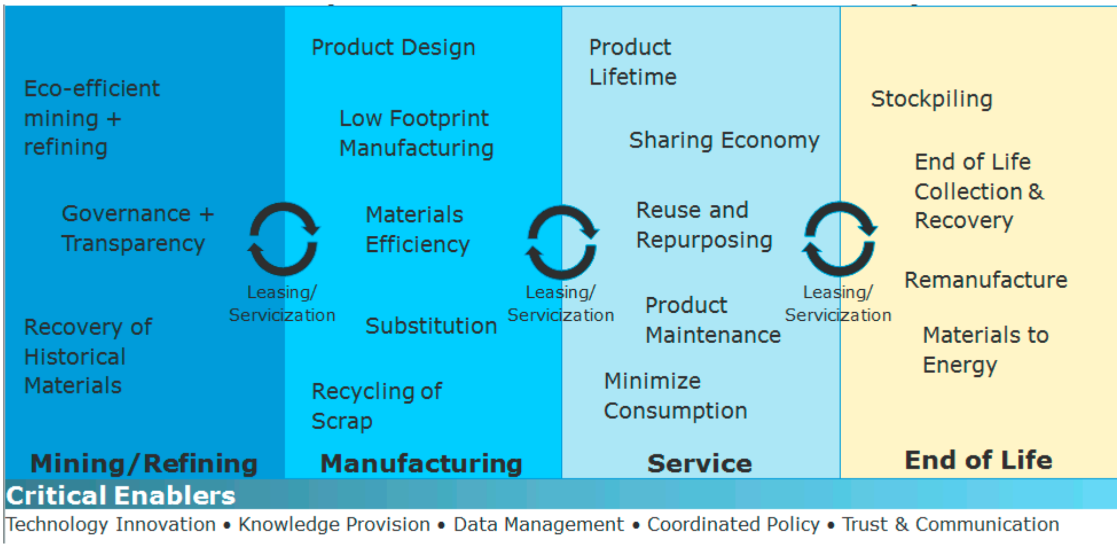

Figure 1. Stewardship activities across the materials lifecycle. Feedback loops between stakeholders provide the opportunity for materials to flow from right to left, as well as left to right.

The lifecycle shown in Figure 1 has been divided into four stages, as adapted from the work of Prior [11]:

(1) Mining and refining of materials produced from either natural capital or anthropic sources (urban mining [12]) or recycled materials;
(2) Manufacturing of products from materials through fabrication, machining, assembly and packaging;
(3) Time in service following distribution of products through the economy via deployment, sales or other business models such as leasing and servicization;
(4) End of life status, in which products may be stockpiled, set aside for collection and recovery, remanufactured, or converted to energy, for example, waste incineration.

2.2. Critical Enablers

Improving the materials efficiency within this lifecycle perspective will require "critical enablers" shown on the bottom of the lifecycle graphic in Figure 1. These include:

(1) *Technology innovation*: Development of new materials with reduced ecological footprint, consuming less energy and using less material to obtain the same function. Technology innovation will also allow for improved recovery of useful materials from waste products and by-products.
(2) *Knowledge provision*: Sharing information between governments, academics, industry and consumers will advance implementation of technology innovations that improve materials efficiency, allow consumers to make more educated choices and empower communities to effectively coordinate their local industries and materials flow cycles to maximize materials sustainability.
(3) *Data management*: Tracking the high volume of materials flowing into, through and out of today's industrialized society will require improved data management and data handling capabilities. As an example, the Sustainable Shipping Initiative began by creating a materials tracking system for monitoring the flow of materials and providing updated inventories so that an initial baseline could be established before undertaking the steps necessary to optimize the materials lifecycles [13].
(4) *Coordinated policy*: Given the number of players involved in the materials lifecycle, policies for extraction of materials from the sources of natural capital, distribution of materials and product

qualification, sale and/or leasing of products on the market, and collection of used products and management of waste streams should be coordinated with the view towards optimizing the overall materials lifecycle, not just individual portions of it. Policies should focus on the "triple bottom line", comprising the total impacts on social, economic and environmental quality. Policies should also be coordinated across the global domain, given the globalization of commerce, not just at the local and national level.

(5) *Trust and communication*: As agreements between materials producers and product manufacturers, and between product manufacturers and end users, take on the shape of service arrangements (stewardship) rather than unidirectional sales (consumption), there will be an increased need to establish trust and communication between those parties. Furthermore, as governance increases with the aim of reaching certain targets for recycling or materials conservation, there will need to develop the corresponding means for verification.

These enablers will give rise to new business models, and these could be built around the idea of leasing and/or servicization models such as Materials as a Service (MaaS) [11]. The drive towards resource efficiency is inevitable given the increases anticipated in global population and the increasing pressure on global resources of not only materials but also the water and energy needed to generate those materials. At the same time, it has been described as the "business opportunity of the century" [14]. Already trends such as the "sharing economy" and "green business" are pointing the way towards the business models of the future [15].

2.3. The Four Ds of Materials Stewardship

With respect to materials science and engineering, we foresee four key categories in which technological innovation can be pursued towards the goal of materials stewardship. We define these four strategies as:

(1) dematerialization;
(2) durability;
(3) design for multiple lifecycles;
(4) diversion of waste streams through industrial symbiosis.

In the following sections, we expand upon each topic in turn and provide some case studies in which current developments across academia and industrial research and development are driving changes, and changing the posture of stakeholders in the materials lifecycle from that of consumer to that of steward.

3. Dematerialization

3.1. Definitions

Dematerialization refers to the reduction in material content of a product. It can also involve the replacement of less sustainable materials with more sustainable materials, either in terms of the embodied energy, or over the lifecycle use of the product. As an example, consider the replacement of steel with aluminum in automotives [16]. This substitution will involve an overall weight reduction, but an increase in the embodied energy of the vehicle due to the higher energy costs of producing aluminum compared to steel. Over the lifetime of the vehicle, however, aluminum will be the more sustainable choice due to the increase in vehicle efficiency (and thus lower energy usage) associated with a lighter weight vehicle. At the same time, given the high recyclability of car steel bodies, the impacts of increasing aluminum content should also be considered with regard to the recycling efficiencies. As this example demonstrates, dematerialization and substitution strategies should be pursued with a comprehensive risk analysis in mind to ensure that the desired gains in sustainability are consistent with expectations and other performance demands on the material.

Advances in materials processing and product design have led to impressive advances in materials performance while reducing the total material content. Aluminum cans and glass bottles, for example, are only a fraction of their weight two decades ago [17]. As a more advanced example, consider the exponential growth of computer processing power afforded with the ability to fabricate materials on smaller and smaller scales.

3.2. Materials Efficiency

Optimization of material efficiency can come about through a number of strategies, summarized in the table below (Table 1). These strategies can be grouped into the categories of Light-weighting, Materials Thrifting, Substitution, Advanced Manufacturing, Combining Services, and Modularization and Standardization.

Table 1. Dematerialization strategies.

Dematerialization Strategy	What Is It?	Where Is It Used?
Light-weighting	Improving operation efficiency through substituting heavier materials with lighter weight alloys or composites	Auto vehicles
		Ship construction
		Subsea risers
Materials Thrifting	Decreasing quantity of material needed to perform a specific function, usually enabled by CAD	Reduction in packaging thickness and shape optimization
		Structural components (panels, beams)
		Nanotechnology
Substitution	Replacing a critical or less sustainable material with a more sustainable choice	Low-footprint manufacturing
		Decarbonification and desulfurization of energy industry
		Non-precious metal catalysts
Eco-Efficient Manufacturing	Production via additive or nanofabrication methods rather than conventional cutting/machining, reducing waste, and only adding material where required by structure and function	Electronics
		Aviation (turbines)
		Automotive
		Engine
		Speciality components
Combining Services	Combining the services of multiple products into one multi-purpose product	Electronics (computers, smart phones)
Modularization and Standardization	Product compatibility eliminating materials redundancy and modularity to improve disassembly, recycling, reuse and repair	Electronics, fasteners, small modular reactors, batteries, consumer products, etc.

3.3. Changing Culture of Consumption

Cultural shifts can lead to changes in the overall consumption of materials by society. In addition, government regulations inevitably play a role in shaping consumer choices via taxation and pricing mechanisms. Likewise, consumer choice regarding product packaging has evolved such that customers increasingly prefer reusable to disposable options. Incentives and user-friendly systems can assist with product reuse through buy-back programs and single-stream recycling such that the extent of new materials introduced to the global flow of materials is reduced. Critical to the widespread adoption of more sustainable technologies is the ability for the new products and materials to perform at the same level or better than old materials, and, for consumer goods, to provide a pleasing aesthetic [14]. Offering customers a sustainability advantage alone is not always enough to differentiate a product from its competitors.

Design and planning at the level of communities can also change the overall society demand for materials. Urban and suburban design can be performed to minimize the needs for car ownership, reduce the quantity of infrastructure needed for roads and the frequency of maintenance, and set building codes that favor sustainable methods and materials of construction [18]. Analogous developments in standards for manufacturing and construction can produce equivalent effects in the industrial world.

4. Durability

4.1. Definition

The second pillar of materials stewardship centers around the concept of durability. Creating products with longer lifetimes, either through design or the application of proper maintenance and inspection procedures, reduces the materials flow required to sustain the services those products provide. Given that building and maintaining infrastructure are some of the biggest contributors to materials flow through society, we focus in this section on the use of concrete and steel in the infrastructure sector.

The durability and reliability of infrastructure has played a very significant role in our history as a society. Roads, highways, tunnels, rails and bridges connect territories that are separated by bodies of water facilitating the access and intercommunication within various communities, contributing to the socio-economic, cultural and educational growth of those locations. Similarly, dams, pipelines, clean water supply and wastewater sewers stimulate the development of society by simplifying its subsistence [19,20]. Since infrastructure is crucial for the transformation of a society, it is generally built to last. The mindset of a durable infrastructure is not new; many infrastructure assets built during ancient times still exist. The increase in population size and use of automobiles for longer commutes mainly in metropolitan areas has demanded bigger, longer, tougher and wider infrastructure to meet societal needs. Material selection, service life extension techniques and maintenance programs tailored to the exposed environment are the keys to long-term preservation of infrastructure.

4.2. Durable Construction Materials

The dominant construction materials in modern infrastructure are concrete and steel. These materials are typically used together as a composite to form reinforced concrete. The embedded steel bars (also known as rebar) into the concrete increase the tensile strength and ductility of concrete. Concrete on the other hand protects the steel from external environmental factors and aggressive species (e.g., chlorides and sulfates). A concrete made with the adequate concrete mix proportions (i.e., cement, water, coarse and fine aggregate, and other chemical admixtures), mixed and cured properly has the materials properties suitable for the construction of large-scale structures as bridges, dams, stadiums, etc. The advantages and disadvantages of reinforced concrete compared to other construction materials (e.g., wood, masonry, metal, alloy, glass, etc.) are listed in Table 2.

Table 2. Reinforced concrete vs. other construction materials.

Advantages	Disadvantages
Durable and minimum maintenance required	Susceptible to cracking due to creep and shrinkage
High compressive and moderate tensile strength	Low strength to weight of concrete ratio
Fire resistant	Cement: world's largest CO_2 producer industry
Steel: world's most recycled material	Steel: susceptible to corrosion

The United States Federal Highway Administration (FHWA) design guidelines require a minimum of 75-year service life for reinforced concrete bridges with minimal maintenance. In fact, newly constructed bridges in the U.S. such as the San Francisco Oakland Bay Bridge in California have been designed to meet a 150-year service life. In other parts of the world, the service life design reaches the 300-year goal such as the Second Gateway Bridge in Australia.

4.3. Challenges to Durable Infrastructure

Achieving long-term durability of bridges can be quite challenging. The bridge design and material selection needs to be tailored to the environmental conditions and aggressiveness at which the bridge will be exposed. In addition, sections of the bridge may be more prone to deteriorate faster than others so other materials should be selected. In addition to that, the maintenance and preservation practices need to be defined. Damage mechanisms of reinforced concrete vary depending on the severity of the environment and the quality of the materials, concrete mix proportions and curing used. Figure 2 lists the most common damage mechanisms of reinforced concrete that lead to failure and significantly reduce the design service life of reinforced concrete bridges [20].

Reinforced Concrete Degradation
Corrosion of rebar
Freeze-thaw deterioration
Abrasion/erosion
Chemical attack
Alkali-silica reaction
Volume changes
Loss of support
Overloads

Figure 2. The most common damage mechanisms of reinforced concrete that lead to failure and reduced service life.

Reinforced concrete deterioration due to corrosion of the embedded steel occurs mainly due the ingress of chloride ions (Cl) and carbon dioxide (CO_2) through the concrete's pore network. Induced cracks will occur once a there is a significant amount of corrosion products at the surface of the embedded steel bar generating sufficient stresses able to exceed the concrete's low tensile strength [21].

Cl ingress is the main contributor to the corrosion of steel in concrete in bridges exposed to marine environments (coastal regions) or to de-icing salts. Cl diffuses to the concrete pores and travels to the concrete cover. Once it reaches the steel bar, the chloride ions accumulate at the surface of the metal, and, when it reaches the chloride corrosion threshold corrosion initiates, this time is known as the time of initiation of corrosion.

In environments with relatively moderate humidity (70%–85%), the concrete pore network is partially filled, allowing CO_2 to ingress and reach the embedded steel bar. This process is known as carbonation, and it consists of the conversion from calcium hydroxide ($Ca(OH)_2$) to calcium carbonate ($CaCO_3$) by the CO_2 ingress from the outside. As a result, the pH of the concrete drops from approximately 12.5 to values lower than 8.5 causing the passive film of the surface of the steel bar to breakdown, which leads to corrosion initiation [21].

4.4. Corrosion Control

Both of the above corrosion-induced mechanisms can take decades to generate a concrete surface damage to a structure. Concrete mix proportions, material selection and quality control are big contributors in the long-term performance of a structure. During the life cycle of a structure, either in the design phase or already in the existing structure, corrosion prevention practices can be implemented. Table 3 describes the most common corrosion prevention practices used today to increase the service life of a structure [22].

Table 3. Achieving long-term durability—corrosion control [22].

New Structures	Existing Structures
Enhanced concrete mix designs: achieve low permeability concretes with low chloride diffusion coefficient	*Cathodic protection*: cathodically polarized the rebars to decrease the corrosion rate
Carbon steel substitutes: replace carbon steel by using other alloys as corrosion-resistant alloys (CRA)	*Coating and Sealants*: protect the surface of the concrete against aggressive species
Cathodic prevention: cathodically polarized the rebars in Cl^- free concrete to increase the chloride corrosion threshold	*Chloride ion extraction*: a technique that consists on applying an electric field at the surface of the concrete to extract the Cl^- by migration
Coatings and sealers: protect the surface of the concrete against aggressive species	

Concrete is typically not considered an "environmental-friendly" material since the cement industry generates approximately 5% of the world's carbon dioxide (CO_2) emissions. In spite of concrete being a composite material that uses a significant amount of water and cement, which generates abundant CO_2 emissions, concrete's life cycle is intended to be durable. And if the structure was properly designed and built, then minimum maintenance will be needed. Steel, on the other hand, is the most recycled material in the world. To enhance the cement properties and to replace cement with other compounds, materials such as fly ash, silica fume, and metakaolin may be added to the concrete mix. Chemical admixtures such as water reducers, corrosion inhibitors, retarding and accelerating admixtures are also used to minimize the water requirements during the concrete mix.

A material that may be suitable to enhance materials properties may not be favorable for other material threats. A simple example is the addition of chloride ions into the concrete mix, and adding chloride ions to the concrete mix proportion may accelerate the curing of concrete and enhance its early strength properties; however, chloride ions can have detrimental effects on the durability. Another example was the use of epoxy-coated steel bars in reinforced concrete. At first glance, it was widely agreed among the reinforced concrete community that the coating protecting the surface of the steel would act as a barrier against aggressive species. Many bridges in the U.S. were built using these types of steel bars during the 1970s and 1980s; however, in places with tropical environments with hot temperatures and relatively high humidity, such as the south region of the State of Florida, significant concrete surface damage occurred in many bridges after less than 10 years of being built [23]. In spite of the promising performance of new emerging cementitious materials, further research is needed to evaluate their service life role. For instance, a concrete with very low permeability and high strength and ductility could result in early cracking, which results in a quicker pathway for aggressive species to reach the steel bar and initiate corrosion faster than other conventional concretes [24].

5. Design for Multiple Lifecycles

5.1. Definition

Consideration of product design is the logical and necessary extension in evaluating how we use materials in our society. There is a tremendous amount of terminology that has surfaced to address the individual concepts that comprise the fundamental idea of 'Design for Sustainability'—Design for Reuse, Design for Serviceability, Design for Environment, etc. Based on some assumptions of scope, Figure 3 provides a hierarchy for classification of each of the different design motivations. In addition, it is also useful to define some of the terms used in these classifications, as they point to specific types of service. First, remanufacturing specifically applies to the service of a product and returning it to its original level of performance, for the original customer, with a warranty that is comparable to that which was provided with the original part [25]. Reconditioning, or refurbishment, refers to returning a used product to acceptable working condition by rebuilding or repairing major components, even before fault. This type of product would have a reduced warranty compared to a new or remanufactured part. These terms demonstrate that a division of expectation and quality of serviced end product is demonstrated, which can be used to determine appropriateness of a given system or product for additional life cycles. It is thus that Design for Multiple Life Cycles is taken as the comprehensive terminology to identify the potential for all kinds of reuse. The following sections will address the two main aspects that characterize and are necessitated by Design for Multiple Life Cycles: evolution of product design practices and adaptation of industrial business models.

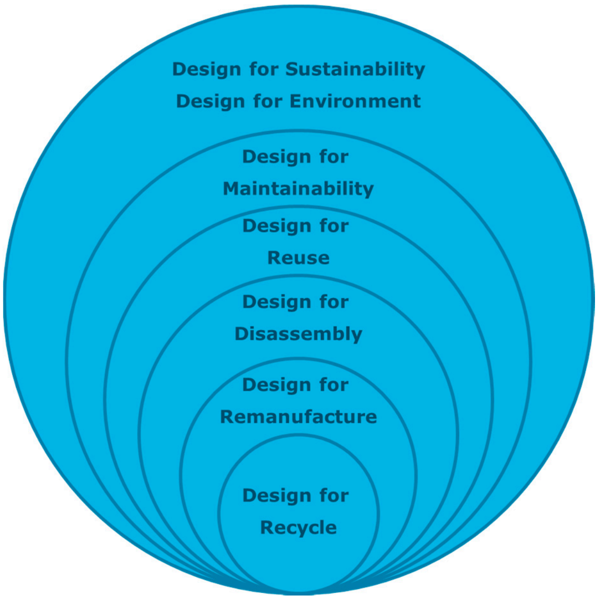

Figure 3. Hierarchy of design principles.

5.2. Components and Complexity

For the purposes of evaluating sustainability and the potential for multiple life cycles, product design is broken down here into two main aspects: design of components and design of whole system. By making this distinction, we can identify where on the hierarchical scale (shown in Figure 3) each component's design philosophy should be placed. Each component within the system has an understood and expected life cycle or failure rate. Pieces such as gaskets and bearings are wear items with minimal opportunity for additional life cycles. Thus, materials selection for these parts should be assessed primarily for opportunities to recycle. At a level of part complexity that is one level higher, we combine multiple components that may contain some of these wear items, as well as some higher value components that may be reused. Thus, we design this item for one level higher in the design philosophy hierarchy—design for remanufacture. Extrapolation of this trend focuses on a direct link between complexity and design philosophy, essentially assuming a direct correlation between manufacturing cost and complexity. In this sense, we arrive at a regimented way to approach these component design philosophies.

The capability for utilizing the above component design philosophies depends on the critical element of whole product design. Serviceable components must be adequately accessible in order to enable cost effective product life cycling. This points to the most fundamental need at the product design level, which is design for serviceability. A survey was conducted by Georgia Tech (Atlanta, GA, USA) on automotive parts remanufacturers—arguably the most effective and active remanufacturing parts industry in the existence—and the specific obstacles they face in servicing parts for multiple life cycles [26]. Parts availability, such as core harvesting programs, or the lack thereof, was cited as the top need. This need points to the importance of involvement of the business case, which is covered in the next section. Beyond parts availability, the ability to disassemble was cited as the primary obstacle to multiple life cycles. Corrosion and rust were identified as the next highest ranking limiting factors, along with the presence of excessive dirt or oil and permanent fastening (glue, welding). With regard specifically to refurbishing and reassembly, employee skill or training was cited as the main obstacle, relating directly to concerns of experience with part design and diversity. Ability to disassemble and permanent fastening are fundamental aspects vital to consider in design for serviceability, and must be put central in product design philosophy. Dirt and oil are cumbersome but can only be addressed to minor extents in the design phase. However, rust and corrosion can be greatly affected by materials selection, and thus should be evaluated in parallel to component design decisions.

5.3. Design of Business Models

As many of the aforementioned conclusions have identified, the success of a multiple life cycle design philosophy is highly dependent on a complimentary business model. Feasibility of such a model requires willingness and cost effectiveness of adopting full life cycle management for a product. Revenue streams have been identified that are capable of justifying obstacles and investment, but these tradeoffs are dependent on the specific product in question. Admittedly, not all products are well-suited to multiple life cycles. Multiple life cycle utilization has proven to be a viable alternative in sectors where it is able to offer high added value products. Table 4 provides some fundamental features of products intrinsically well-suited to remanufacture or reuse.

Table 4. Guidelines for identifying features and detriments to the suitability of a product for consideration of multiple life cycle design. Reproduced with permission from Remanufacturing, UK (with thanks to David Parker) [25].

Beneficial Features	Detrimental Features
High intrinsic value	Poor design for assembly/disassembly
Good durability	Proliferation of materials in construction
Low to moderate technological evolution	Status-dependent fashionable items
Core readily available	Poor perception of standards/branding
Integrated sales/service/upgrade options	Low price of new goods
Design information available	Craft skill shortage

One product currently being investigated for second life potential is the lithium ion battery. Lithium ion batteries in the automotive and other sectors are already becoming ubiquitous [27]; however, the economics are not yet in favor of widespread recycling, although innovation also continues in this area [28]. Hence, second use becomes a more appealing possibility, especially given the large energy potential remaining in batteries following their primary use in an automobile (up to 70% capacity) [29]. In order to enhance the potential for second life use of batteries, innovations need to be made in assessing the remaining health and safety status of used batteries, and simplifying the process of disassembly and remanufacture. These barriers to second life adoption could be streamlined by taking second life into account at the design stage.

Having an effective business model stems from engagement of the Original Equipment Manufacturer (OEM). The OEM will represent either the key facilitator or the primary obstacle to additional life cycles because they control the original design philosophy and thus the opportunity to connect design and remanufacture opportunities. Markets for second life products must be established, and these products will compete with first life manufactured products; success in such a competitive environment relies heavily on the specific product, and thus those aspects cited in Table 4.

The typical reaction is to implement policies requiring remanufacturing efforts or multiple life cycle considerations. However, it is feasible, more efficient and more economically sustainable to instead limit barriers to remanufacturing and reuse. One aspect is to support a freedom of knowledge policy to simplify and mitigate barriers to remanufacturing, and this also opens up the competitive landscape by enabling third parties to act as remanufacturing entities. Of course, this should be coupled with conscientious avoidance or removal of legal restrictions that burden components that would otherwise be indistinguishable from new.

The most attainable and enabling—as well as necessary—business or marketing tool that can be used to encourage any of the multiple life cycle concepts mentioned is the implementation of a core collection program. Identifying entities in the supply chain that can be cost effectively incentivized provides an excellent assessment of feasibility of implementing such a business case. Cores, as identified in surveys, consist of the most fundamental enabling piece of the puzzle—as well as the most potentially cumbersome. The availability of intermediaries to collect and convey cores, combined with the willingness of OEMs to pursue full life cycle revenue streams may provide the first steps to habitual adoption of multiple life cycle consumer products.

6. Diversion of Waste Streams through Industrial Symbiosis

6.1. Definition

By-products of industrial processes such as the manufacturing of goods, the refining of metals or the production of energy are often of little or no economic value and so redirected to the landfill or, in the case of fluids, stored in pools or emitted to the environment. Technological innovation and strategic partnerships, however, can potentially improve the stewardship of these waste materials through providing economic value by using waste streams as feedstocks for the production of new materials. As an example, consider CO_2 utilization to produce fuels vs. CO_2 sequestration.

6.2. Utilization of Carbon Waste Streams

Carbon utilization technologies vary according to the volume of CO_2 utilised, the economic value of the end product (i.e., value added) and the time of fixation of CO_2. Carbon Capture and Storage (CCS) can potentially store large volumes of CO_2 in geological media for hundreds of years, but without significant monetary gain. Cements and minerals made from CO_2 can provide some monetary value, and this process is able to convert relatively large volumes of CO_2. Specialty organic chemicals and polymers provide high value-added products and can fix CO_2 within the products over relatively long time periods, but their volumes are rather small compared to the magnitude of emitted CO_2. Fuels have a very short fixation time, emitting CO_2 as soon as they are burned. However, they add significant value because they contribute to energy storage from renewable power and provide energy security. Fuels made from CO_2 can provide high volume fixation with moderate profitability (Figure 4). It is already recognized that biofuels from photosynthetic plants and organisms have the potential to substantially reduce net life cycle CO_2 emissions.

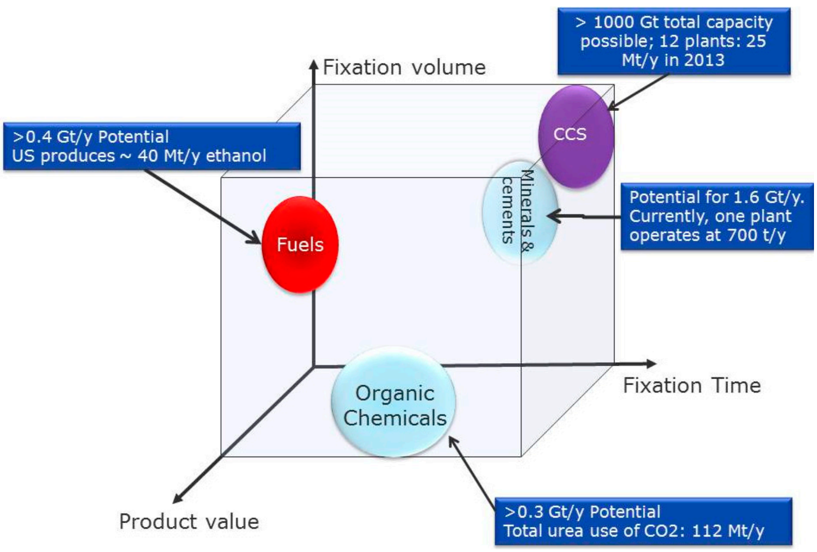

Figure 4. Value vs. fixation time vs. fixation volume for carbon dioxide storage vs. utilization strategies.

As an example, consider a strategy that involves the electrochemical reduction of CO_2 conversion into ethanol via formic acid and methanol [30,31]. The traditional corn-based ethanol process emits about 2.6 mole of CO_2 per mole of ethanol (or about 70 g of CO_2 equivalent /MJ). This does not include the CO_2 emitted upon use in the internal combustion engine. In contrast, the electro-biochemical route of ethanol from CO_2 and methane could involve a net consumption of CO_2 of the order of 3 million tons per year even using fossil-based power. The net reductions can be increased if a greater percentage of renewable power is used.

6.3. Industrial Symbiosis

As another example of the diversion principle, consider the development of industrial symbiosis networks. Often geographically co-located as local or regional "industrial parks", these networks facilitate the exchange of by-products and waste streams to minimize net waste through profitable economic interactions. Very recently, algorithms have been proposed to develop artificial intelligence "agents" to assist in the construction of industrial symbiosis networks [32]. The US Business Council for Sustainable Development has also worked with various states to create "By-product Synergy networks" that function in the same way [33]. Keeping with the themes of CO_2 and concrete, an analysis of the cement industry has shown that when cement producers are co-located with energy and steel industries, for example, there is enhanced potential for more sustainable practices such as including waste streams from the latter industries (such as fly ash) into blended cements as well as utilizing waste heat and/or using renewable energy [34].

6.4. Single-Stream Recycling

Innovations in the sensing and sorting of materials have greatly facilitated post-consumer recycling capabilities by allowing for a single stream process [35]. Allowing for single stream processing removes the burden of separating incompatible materials by the consumer, who is not always prepared to be the best steward of the materials that flow through their household systems (not just due to lack of education, but also due to the fast pace of change in the materials composition of consumer goods and the difficulty associated with recognizing materials composition from simple user inspection). Nowadays, it is routine for community recycling facilities to use magnetic, eddy current, and gravity assisted systems for sorting between various steel, aluminum, plastic and paper goods. Challenges still remain and require "human sorting" to eliminate items that remain uneconomical to recycle (such as composite materials like foil-lined food packaging), or are deleterious to the single stream sorting system (such as plastic bags that can snag in conveyor system rollers, for example). At the same time, technological innovations are bringing new sensor technologies online to further identify and separate materials from waste flow streams.

7. Quantifying Stewardship

Predictions of materials' supply constraints using reserve to demand ratios or Hubbert curves suggest that, within decades, we will be running up against planetary boundaries for several materials of industrial importance such as nickel, copper, and precious metals [36,37]. At the same time, tracking historical trends in these predictions reveals that the estimated reserves are a "moving target" and that there is a considerable band of uncertainty surrounding these predictions [3]. This uncertainty, coupled with increasing demand with the rise of the developing world, will likely result in increasing supply chain volatility—in the worst case, increasing costs as exploration and production become more challenging once the economical reserve base is depleted. As Figure 5 demonstrates, production of a variety of industrially critical elements, including iron, chromium, nickel, platinum, niobium, lithium and copper has increased at an exponential pace throughout the 20th century. Materials' stewardship strategies in the 21st century should focus on decreasing this pace of consumption through the 4D strategies outlined in this paper.

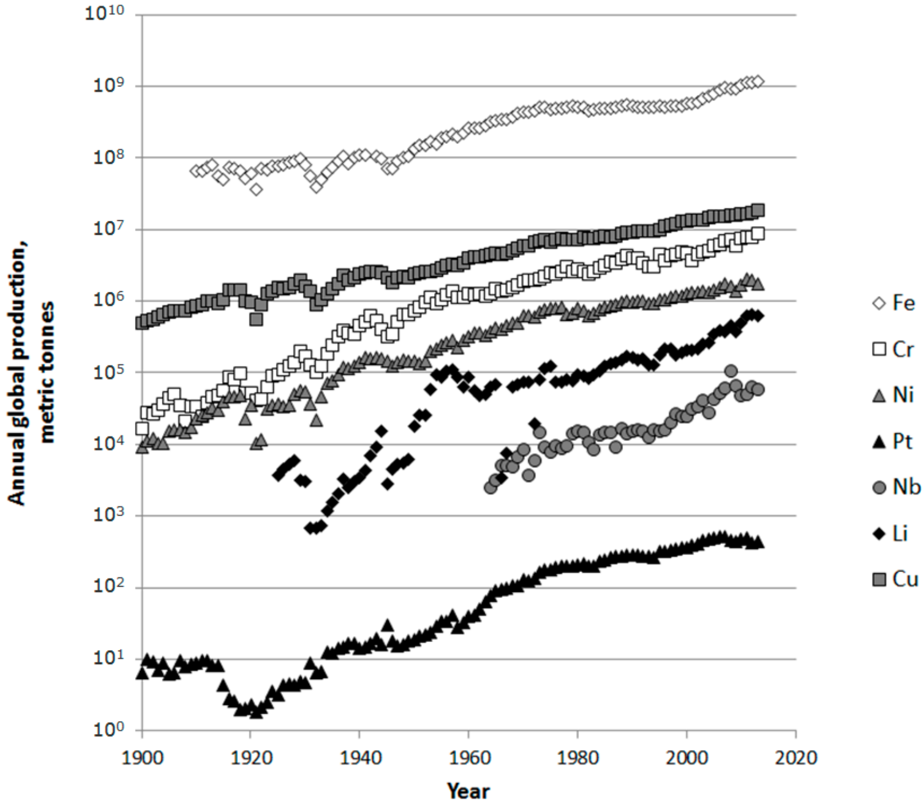

Figure 5. World production of several industrially critical materials as estimated from United States Geological Survey data [38].

From a mathematical standpoint, the rate of materials extraction is given by the expression:

$$\frac{dM_N}{dt} = \frac{dM_s}{dt} + \frac{dM_x}{dt} - \frac{dM_R}{dt},$$

where the term on the left-hand side is the rate of materials extraction from the natural world (i.e., the quantities shown in Figure 5), and the terms on the right-hand side are the rate of societal demand, the rates of materials loss due to waste or degradation, and the rate of recycling, respectively. At the individual, state and community levels, the various stewardship strategies can be applied to reduce the rates of materials extraction from the natural world. That is, dematerialization and design strategies can decrease the societal demand $\frac{dM_s}{dt}$, durability strategies can reduce losses $\frac{dM_x}{dt}$, and diversion of waste (and design for multiple lifecycles) can increase the rate of recycling $\frac{dM_R}{dt}$. Adopting materials accounting strategies such as materials flow accounting [39] is important to quantifying the gains that are made through these strategies, in order to ensure that systematic and reliable improvements are being made and strategies adapted to further optimize their impact in response to lessons learned.

8. Conclusions

The materials stewardship strategies outlined in this paper provide individuals, business and states with tools mitigating risk exposure associated with materials utilization and dependency. Considerable advantages can be obtained by attending to materials efficiency. Not only reduction of waste, but the ongoing efforts to engage lower cost substitute materials for those with high process requirements or supply limitations will provide businesses with opportunities to lower costs of operation, and increase flexibility to develop new products and services for their customer base. The ability to utilize substitute materials will improve manufacturing agility, especially as the demand expected to take hold over the coming decades will result in rising commodity prices set against more extremes of price volatility.

Preserving resources for the generations of tomorrow while meeting the needs of the present [40] necessitates the use of models to predict both trends in materials' availability [36,37,41] as well as changing patterns of future consumption [18]. In addition, it requires a better assessment of the way and quantity in which materials are currently used today. These sustainability models can then be used to guide decision making, and to spawn research among the topics of dematerialization, design for multiple life cycles, diversion of waste streams, and durability, to seek an optimum path that ensures both short-term and long-term prospects.

Critical enablers will be found through inculcation of a stewardship culture across company hierarchies, technological innovation, modeling and optimization of materials flows, and data management to monitor the materials' lifecycles. Pursuing these goals, alongside new materials discovery and resource exploration, advanced strategies for environmental management and remediation that enrich biodiversity and ecosystem health, in addition to seeking ways to serve the growing developing world with an expanding middle class, will enable the flourishing of a safe and sustainable future.

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References

1. United Nations General Assembly. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sustainabledevelopment.un.org/post2015/transformingourworld (accessed on 28 June 2016).
2. Bardi, U. *Extracted*; Chelsea Green Publishing: White River Junction, VT, USA, 2014.
3. Smil, V. *Making the Modern World*; John Wiley & Sons: West Sussex, UK, 2014.
4. Hammond, K.; Mishra, B.; Apelian, D.; Blanpain, B. CR3 communication: Red mud—A resource or a waste? *JOM* **2013**, *65*, 340–341.
5. Ghosh, B.; Ghosh, M.K.; Parhi, P.; Mukherjee, P.S.; Mishra, B.K. Waste printed circuit boards recycling: An extensive assessment of current status. *J. Clean. Prod.* **2015**, *94*, 5–19. [CrossRef]
6. United States Environmental Protection Agency. Advancing Sustainable Materials Management: Facts and Figures 2013. 2015. Available online: https://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report (accessed on 28 June 2016).
7. Apelian, D. Materials science and engineering's pivot role in sustainable development for the 21st century. *MRS Bull.* **2012**, *37*, 318–323. [CrossRef]
8. International Council on Mining & Metals. Maximizing Value: Guidance on Implementing Materials Stewardship in the Minerals and Metals Value Chain. 2006. Available online: https://www.icmm.com/en-gb/publications/maximizing-value-guidance-on-implementing-materials-stewardship-in-the-minerals-and-metals-value-chain (accessed on 28 June 2016).
9. MacArther, E.; Zumwinkel, K.; Stuchtey, M.R. Growth within: A Circular Economy Vision for a Competitive Europe, Ellen MacArthur Foundation. 2015. Available online: http://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf (accessed on 29 August 2016).
10. Ignatenko, O.; van Schaik, A.; Reuter, M.A. Exergy as a tool for evaluation of the resource efficiency of recycling systems. *Miner. Eng.* **2007**, *20*, 862–874. [CrossRef]
11. Prior, T.; Giurco, D.; Mudd, G.; Mason, L.; Behrisch, J. Resource depletion, peak minerals and the implications for sustainable resource management. *Glob. Environ. Chang.* **2012**, *22*, 577–587. [CrossRef]

12. Jones, P.T.; Geysen, D.; Tielemans, Y.; Pontikes, Y.; Blanpain, B.; Mishra, B.; Apelian, D. Closing materials loops: The enhanced landfill mining concept. *JOM* **2012**, *64*, 743–744.
13. Sustainable Shipping Initiative. Driving Transformational Change through the Value Chain. 2014. Available online: http://www.ssi2040.org/wp-content/uploads/2015/04/SSI-Global-Trends-Digital-Final-Report.pdf (accessed on 28 June 2016).
14. Heck, S.; Rogers, M. *Resource Revolution*; Melcher Media: New York, NY, USA, 2014.
15. Hawken, P.; Lovins, A.; Lovins, L.H. *Natural Capitalism*; Little, Brown and Company: New York, NY, USA, 1999.
16. Daehn, G.S. *Sustainable Design and Manufacture of Lightweight Vehicle Structures, Alternative Fuels and Advanced Vehicle Technologies*; Folkson, R., Ed.; Woodhead Publishing: Cambridge, UK, 2014.
17. Unilever PLC. Sustainable Packaging? 2009. Available online: https://www.unilever.com/Images/sd_sustainable-packaging--2009-_tcm13-387437_tcm244-409779_1_en.pdf (accessed on 27 September 2016).
18. Odum, H.T.; Odum, E.C. *A Prosperous Way Down*; University Press of Colorado: Boulder, CO, USA, 2001.
19. Khatib, J. *Sustainability of Construction Materials*; Woodhead Publishing Limited: Cambridge, UK, 2009.
20. Mindess, S.J.; Young, F.; Darwin, D. *Concrete*, 2nd ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2003.
21. Bertolini, L.; Elsener, B.; Pedeferri, P.; Redaelli, E.; Polder, R.B. *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
22. Hartt, W.H.; Powers, R.G.; Leroux, V.; Lysogorski, D.K. *Critical Literature Review of High-Performance Corrosion Reinforcements in Concrete Bridge Applications*; Publication Number: FHWA-HRT-4-093; Florida Atlantic University: Dania Beach, FL, USA, 2004. Available online: https://www.fhwa.dot.gov/publications/research/infrastructure/structures/04093/04093.pdf (accessed on 28 June 2016).
23. Sagüés, A.A.; Lau, K.; Powers, R.G.; Kessler, R.J. Corrosion of epoxy-coated rebar in marine bridges—Part 1: A 30-year perspective. *Corrosion* **2010**, *66*, 065001.1–065001.13. [CrossRef]
24. Sagues, A.A. Modeling the effects of corrosion on the lifetime of extended reinforced concrete structures. *Corrosion* **2003**, *59*, 854–866. [CrossRef]
25. Chapman, A.; Bartlett, C.; McGill, I.; Parker, D.; Walsh, B. *Remanufacturing in the UK*; A Report Supported by Biffaward through the Landfill Tax Credit Scheme and Part-Sponsored by South East England Development Agency (SEEDA); Resource Recovery Forum: Skipton, UK, 2010.
26. Hammond, R.; Amezquita, T.; Bras, B. Issues in the automotive parts remanufacturing industry—A discussion of results from surveys performed among remanufacturers. *EDA* **1998**, *4*, 27–46.
27. Block, D.; Harrison, J.; Brooker, P. *Electric Vehicle Sales for 2014 and Future Projections*; Florida Solar Energy Center Report Number: FSEC-CR-1998-15; Florida Solar Energy Center: Cocoa, FL, USA, 2015.
28. Zou, H.; Gratz, E.; Apelian, D.; Wang, Y. A novel method to recycle mixed cathode materials for lithium ion batteries. *Green Chem.* **2013**, *15*, 1183–1191. [CrossRef]
29. Elkind, E. *Reuse and Repower*; Emmett Institute on Climate Change and the Environment: Berkeley, CA, USA, 2014.
30. Agarwal, A.S.; Rode, E.; Sridhar, N.; Hill, D. Conversion of CO_2 to value-added chemicals: Opportunities and challenges. In *Handbook of Climate Change Mitigation and Adaptation*; Chen, W.-Y., Suzuki, T., Lackner, M., Eds.; Wiley & Sons: Hoboken, NJ, USA, 2015; pp. 1–40.
31. Agarwal, A.S.; Zhai, Y.; Hill, D.; Sridhar, N. The electrochemical reduction of carbon dioxide to formate/formic acid: Engineering and economic feasibility. *ChemSusChem* **2011**, *4*, 1301–1310. [CrossRef] [PubMed]
32. Bichraoui, N.; Guillaume, B.; Halogb, A. Agent-Based modelling simulation for the development of an industrial symbiosis. *Procedia Environ. Sci.* **2013**, *17*, 195–204.
33. U.S. Business Council for Sustainable Development. The Materials Marketplace. Available online: http://usbcsd.org/materials/ (accessed on 29 September 2016).
34. Ammenberg, J.; Baas, L.; Elkund, M.; Feiz, R.; Helgstrand, A.; Marshall, R. Improving the CO_2 performance of cement, part III: The relevance of industrial symbiosis and how to measure its impact. *J. Clean. Prod.* **2015**, *98*, 145–155. [CrossRef]
35. Reuter, M.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hageluken, C. *Metal Recycling: Opportunities, Limits, Infrastructure*; International Resource Panel Report; United Nations Environment Program: Nairobi, Kenya, 2013.

36. Bardi, U. The mineral economy: A model for the shape of oil production curves. *Energy Pol.* **2003**, *33*, 53–61. [CrossRef]
37. Arndt, R.A.; Roper, L.D. *The Metals and Mineral Fuels Crises, Facts and Predictions*; University Publications: Blacksburg, VA, USA, 1977.
38. Kelly, T.D.; Matos, G.R. *Historical Statistics for Mineral and Material Commodities in the United States*; Supersedes Open-File Report 01-006; U.S. Geological Survey: Reston, VA, USA, 2014. Available online: http://minerals.usgs.gov/minerals/pubs/historical-statistics/ (accessed on 28 June 2016).
39. Haberl, H.; Fischer-Kowalski, M.; Krausmann, F.; Weisz, H.; Winiwarter, V. Progress towards sustainability? What the conceptual framework of material and energy flow accounting has to offer. *Land Use Policy* **2004**, *21*, 199–213.
40. Brundtland, G.H. *Our Common Future*; Report of the World Commission on Environment and Development; United Nations World Commission on Environment and Development: Oslo, Norway, 1987.
41. Randers, J. *2052*; Chelsea Green Publishing: White River Junction, VT, USA, 2012.