Material efficiency in a multi-material world

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Material efficiency—using less of a material to make a product or supply a service—is gaining attention as a means for accomplishing important environmental goals. The ultimate goal of material efficiency is not to use less physical material but to reduce the impacts associated with its use. This article examines the concept and definition of material efficiency and argues that for it to be an effective strategy it must confront the challenges of operating in a multi-material world, providing guidance when materials are used together and when they compete. A series of conceptions of material efficiency are described, starting with mass-based formulations and expanding to consider multiple resources in the supply chain of a single material, and then to multiple resources in the supply chains of multiple materials used together, and further to multiple environmental impacts. The conception of material efficiency is further broadened by considering material choice, exploring the technical and economic effects both of using less material and of materials competition. Finally, this entire materials-based techno-economic system is considered with respect to the impact of complex policies and political forces. The overall goal here is to show how the concept of material efficiency when faced with more expansive—and yet directly relevant—definitional boundaries is forced to confront analytical challenges that are both familiar and difficult in life cycle assessment and product-based approaches.

1. Introduction

Material efficiency is a concept and agenda that can complement the more familiar strategy of energy efficiency as a means for accomplishing important environmental goals [1]. Material efficiency can be
succinctly described as using less of a material to make a product or supply a service. Common examples include designing a plastic bottle to have a lighter cap, or reducing the amount of pulp required to make a ream of office paper. While such notions are commonplace in environmental discourse and practice, recently efforts have been made to reinvigorate this approach to environmental improvement [1].

The proponents of material efficiency distinguish it from two related concepts. Resource efficiency, a strategy and concept widely discussed in many policy making venues from the Organisation for Economic Cooperation and Development (OECD) to national to regional and local governments, is differentiated from material efficiency and defined as the pursuit of efficiency where all resources are measured with a single weight measure. Product-based approaches, anchored in life cycle assessment (LCA), are also distinguished.

The terminology here is, as is often the case in environmental discourse, inconsistent across authors and institutions. The terms resource productivity and sustainable materials management (SMM), are also widely used with regard to improved use of materials and generally correspond to resource efficiency. Resource productivity and resource efficiency typically take a macro perspective and emphasize linkages to natural resources while SMM operates at multiple levels and has a strong policy orientation. Product-based approaches in this domain nearly always entail a life cycle framework; in the policy arena this takes the form of integrated product policy [6]. In the management arena, it is life cycle management [7]. Sitting roughly between these two competing frameworks, material efficiency builds in part on a foundation in materials science with an emphasis on the physical character of specific materials.

2. Premises and goals of material efficiency

Three of the core premises of material efficiency are important to this exploration. The first is that materials can be used more efficiently—that there are opportunities to be exploited. The second is that material efficiency is understudied. The third is that significant environmental gains can be realized through increased material efficiency.

Allwood et al. [1, p. 362] describe material efficiency as ‘a set of opportunities… that might provide a significant reduction in the total environmental impact of the global economy, but which are under-developed’. A variety of carefully delineated examples of opportunities for increased material efficiency in the use of steel and aluminium are presented in a recent textbook by Allwood & Cullen [8]. More broadly, a series of strategies are catalogued by these same authors including improved yield, increased recycling, decreased consumption, lengthened product life spans, intensified use, repair and resale; increased product upgrade, modularity and remanufacturing; increased component reuse and light weighting [1]. Quantification of potential aggregate improvement from improved material efficiency is understandably very difficult to estimate because of the diverse range of activities and industrial sectors involved and because isolating the impacts of the strategies and avoiding double-counting is daunting.

These same authors argue that, while attention to material efficiency was routine prior to the industrial revolution, it has been eclipsed by attention to energy efficiency within environmental policy and management. Furthermore, it is deliberately sacrificed in practice when the costs of labour exceed the cost of raw materials in industrial production [8]. Academic attention is meant to address the former source of neglect. Growing recognition of climate change risks and similar threats is meant to alter the second.

An important challenge facing a material efficiency strategy lies in going beyond mass-based savings of materials to ensure that any such gains contribute to underlying environmental goals. That is, the ultimate goal of material efficiency is not to use less physical material but to reduce

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1 See reports, for example, by the OECD [2], US Environmental Protection Agency [3] and the British Cabinet Office [4].

2 Efficiency and productivity are not synonymous, but, in this context, the relevant literatures do not draw important distinctions between them. For a discussion of the relationship of sustainable materials management to resource productivity and related concepts, see the study by Brady [5].
the impacts associated with its use. For material efficiency to be an effective strategy, it must confront the challenges of operating in a multi-material world—providing guidance to designers, managers, policy-makers and the like when materials are used together and when they compete. We argue that these challenges naturally lead to considering material efficiency in a context that includes multiple materials and multiple impacts, and that reflects the techno-economic and political interlinkages among materials in the global economy.

This paper builds to this final, systems-level perspective in several steps (figure 1). First, we discuss the standard mass-based formulation of material efficiency and its relationship to similar measures of environmental or engineering performance. Next, we expand the discussion to consider multiple resources in the supply chain of a single material, and then to multiple resources in the supply chains of multiple materials used together—that is, a product supply chain. These are all mass-based discussions, and subsequently other environmental impacts are considered, both in single- and multi-attribute tools, notably LCA. The paper then shifts to explore material efficiency in terms of material choice, exploring both the technical and economic effects of using less material and of materials competition. Finally, this entire materials-based techno-economic system is considered with respect to the impact of complex policies and political forces. The overall goal here is to show how the concept of material efficiency when faced with more expansive—and yet very directly relevant—definitional boundaries is forced to confront difficult and familiar challenges.

3. The basic formulation of material efficiency

The basic and most commonly used formulations of material efficiency consider a single material, using mass, economics or thermodynamics as a basis for appropriate metrics. On a mass basis,
material (mass) efficiency $\eta_m$ is simply the ratio of material that is used ($M_p$) to the material that is supplied ($M_s$):

$$\eta_m = \frac{M_p}{M_s}. \quad (3.1)$$

This expression is identical to the yield, and can be applied to any particular step of material production, or to the production system as a whole. In the case of metals, for example, $\eta_m$ might be the ratio of iron contained in ore inputs to the liquid metal coming out of a blast furnace, or it could be the ratio of all iron mobilized by anthropogenic means to that actually put into service in products. This is the formulation employed by Allwood et al. [8], who describe a mathematical framework for estimating the environmental impacts of producing and processing a specific material:

$$C = D \times \frac{M_p}{D} \times \frac{M_s}{M_p} \times \frac{C}{M_s}, \quad (3.2)$$

where $C$ is the total emissions (or impacts, more generally), $D$ the total number of goods that contain the material, $(M_p/D)$ the amount of material per good and $(C/M_s)$ the average emissions (impacts) per unit of material supplied. $(M_s/M_p)$ is the inverse of yield and indicates the amount of material contained in a product relative to the amount supplied as an input.

Such a definition takes an engineering or industrial ecology perspective, that is, one centred on physical flows of materials and energy. An economist would frame this differently. The question could be posed as one of technical efficiency, allocative efficiency or productivity. A process is technically efficient if the maximum physical output is obtainable from a given input level. Allocative efficiency moves beyond physical and technical relationships to incorporate costs, prices and profits. With respect to materials, allocative efficiency involves selecting that mix of inputs that produces a given quantity of output of goods and services at minimum cost [9]. Productivity differs in that it also accounts for scale economies [10]. Put another way, efficiency holds production constant while optimizing the input mix, productivity holds inputs constant and evaluates production results under different conditions.

A body of research in industrial ecology and environmental economics explores the efficiency of firms with respect to environmental performance, especially emissions [11–15]. Production efficiency models based on ‘production frontiers which define a benchmark relationship between inputs and outputs’ [12] can use data envelopment analysis and stochastic frontier analysis to quantify the gap between existing and desired performance in ways that incorporate not only pollution, but also inputs. Frontier-based analysis often examines total factor productivity, but can also be used to assess individual inputs.\(^3\)

A third approach to measuring the efficiency of producing a single material is an energy perspective based in thermodynamics. One formulation of the second law of thermodynamics states that there is a minimum amount of energy required to transform a substance from its natural state (such as carbon in oil in the ground) to a more industrially useful state (such as carbon in thermoplastics). In a literature going back decades, researchers have tracked the progress of energy efficiency in industrial processes, as energy usage approaches thermodynamic limits, coming within a few percent in some cases [17,18].

\(^{(a)}\) Extending material efficiency to multiple resources in the supply chain

A mass-based conception of material efficiency limited only to one material—for example, the amount of iron used in a product relative to that which is extracted from the Earth—can be enriched by including the mass of all materials mobilized or perturbed in the quantification of the material flows associated with a specific material. Calculated this way, material efficiency includes both deliberately used non-target materials (e.g. ancillary materials used to produce the target material) and non-useful materials mobilized during resource extraction known as hidden flows (e.g. waste rock or gangue generated during mining). If we think of $C$ in solely

\(^3\)In the environmental context, see, for example, the study of nutrient inputs in beet farming by De Koeijer [16].
material terms as the total amount of matter mobilized to produce the material in question, then material efficiency is the same as resource efficiency; it is a mass-based indicator. When used at an economy-wide level to quantify the mass flows associated with a given economy or sector, this multi-material metric is known as total materials requirement (TMR) and includes all materials viewed together [19,20]. TMR can, however, be narrowed to the quantification of all materials mobilized in the performance of a specific task: material input per service (MIPS) [21]. One could also imagine a metric similar to MIPS that quantifies the materials mobilized when using a particular amount of a specified material. Such a metric would be focused on a target material, measured in mass but would encompass all related material flows.4

One reason to consider material efficiency in this way is that it allows us to investigate the unintended consequences of certain efficiency strategies, such as dematerialization or substitution of one material with another. Such strategies can reduce the physical amount of material that is incorporated into a given product; however, this must be done with an eye on ‘non-target-material’ impacts, as the following example shows.

Consider a nickel-based catalyst used for petroleum refining. One option for dematerializing this product is to produce nanostructured catalysts with high specific surface area, which preserves the number of reactive sites (and therefore the functionality of the catalyst) while drastically decreasing the total amount of nickel used. On the face of things, this would seem to increase material efficiency. As previous research has shown, however, the sheer mass of direct auxiliary materials (such as washing agents) needed in nanomaterial production can be orders of magnitude larger than that needed to process bulk industrial materials, to say nothing of the indirect mass needed to produce these auxiliary materials [22], as well as energy inputs. Another option might be to choose a different, more effective catalyst, say rhenium, which requires less final material. The downside of this choice is that rhenium is one of the rarest elements on the planet and occurs in extremely low concentrations in ores, requiring a correspondingly large amount of crude material processing [23], so that switching from nickel to rhenium may actually increase the amount of upstream industrial processing (and the associated resource inputs and impacts) needed to provide the catalyst.

4. Extending mass-based material efficiency to multiple impacts

(a) Environmental extensions

To the extent that material efficiency is motivated by concerns other than resource scarcity, C typically designates greenhouse gases or energy consumption. As noted earlier, such environmental impacts are, in fact, a core motivation in the literature on material efficiency.5

The discussion above hints at the ways in which the use of a specific material may entail the mobilization of many resources. The picture becomes further complicated when C is multi-dimensional, that is, when, for example, multiple environmental impacts are incorporated into the definition of material efficiency. We might call this environmental efficiency or, more precisely, environmentally calibrated material efficiency.6

It is easiest to choose a single, important category of impacts (such as energy use or greenhouse gas emissions) as a basis for efficiency targets [8], and this is also the approach frequently taken by governments as it leads to clearer policy implementation. When it is important for strategic or policy reasons to consider more than one measure of efficiency, multi-attribute tools are frequently

4 Such a metric can be derived from input–output tables. Note that MIPS, as currently formulated, aggregates inputs, and hidden and end of life flows into five categories: biotic resources; abiotic resources; Earth movements in agriculture and silviculture; water; and air. The approach sketched here would thus be an extension.

5 Allwood et al. [1] explicitly reject resource scarcity as a motivation for material efficiency.

6 This is somewhat similar to the variant of eco-efficiency called environmental productivity [24]. However, eco-efficiency is an empirical relation in economic activities between environmental cost or value and environmental impact [25], whereas material efficiency is a biophysical input–output relation.
employed. Trade-offs can occur among multiple materials, but also among different measures of efficiency or impact. For example, polyester fibres are produced in high-yield reactions from their petrochemical precursors and are thus material efficient on a mass basis, but are depleting of fossil resources. On the other hand, cotton as an agricultural fibre is not directly derived from fossil resources, but requires high levels of water use and pesticide application, and has a comparatively low material efficiency, as only a portion of the plant is incorporated into saleable products [26].

The incorporation of multiple environmental impacts into the assessment of material efficiency leads nearly inexorably to LCA. Widely used in the assessment of materials and products, LCA ‘quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with the entire life cycle of any goods or services’ [27]. It is generally viewed as a tool for environmental assessment. In this context, three characteristics are worth noting because they highlight the expansion of the definition of material efficiency explored here. First, LCA is multi-attribute, seeking to assess multiple environmental impacts simultaneously, even comprehensively. Second, like MIPS, but unlike some other assessment tools, it revolves around the definition of a functional unit. In order to conduct an LCA, one must define the service being delivered; otherwise any comparisons of interest are, prima facie, misleading. And, third, it entails a life cycle framework, broadening any assessment beyond individual processes in the product chain. The assessment of multiple impacts and definition of a system boundary beyond individual processes reflect the quest for a systems perspective or even a sort of technical holism that is simultaneously LCA’s appeal and the source of many of its technical challenges.

The requirement of a functional unit can be sidestepped without abandoning the other aspects of LCA, that is, the cradle to grave assessment of resource consumption and emissions can be conducted on a mass or unit basis as long as the inferences drawn from the results are appropriately constrained. Life cycle inventory and impact assessment data can also be combined with material flow models to give measures of environmentally weighted material consumption across multiple materials and at regional scales. For example, van der Voet et al. [28] examined the largest material flows in the Dutch economy both in terms of mass and in terms of 13 impact categories, estimating the total impacts due to the overall use of materials in The Netherlands. Conversely, Eckelman & Chertow [29] examined the total reduction in various environmental impacts due to the reuse of industrial materials in the US state of Pennsylvania, finding the benefits in terms of reduced demand for primary energy exceeded all (non-hydro) renewable energy generation [29].

Other variants of these approaches exist. For example, DeWulf & Van Langenhove [30] modify the notion of MIPS to incorporate calculation of both resource input and service output in exergy terms, calling their metric exergetic material input per unit of service, putting thermodynamic concepts of efficiency on functional unit basis.

(b) Economic extensions

Impact categories also need not be strictly environmental. In economic terms, efficiency is formulated as the economic benefits delivered by a unit of material, while eco-efficiency metrics scale or discount these economic benefits with the associated environmental costs of each material [25]. As with physical formulations of material efficiency, economic efficiency and eco-efficiency (with respect to materials) are typically measured for a single material. Some authors have argued that applying eco-efficiency metrics across fundamentally different materials, or in multi-material products, can lead to recommendations that ignore the physical basis of those materials [31]. Returning to the example of cotton versus synthetic textiles, material efficiency matters less for resource sustainability in the case of cotton because it is a renewable material, whereas efficiency targets may be appropriate to help ensure the availability of polyester based on fossil petroleum in the medium term. While these arguments were made with specific reference to eco-efficiency models, these considerations are equally pertinent for other formulations of material efficiency.
Any assessment of efficiency improvements arising from material substitution depends on (among other things) the definition of efficiency. A mass-based comparison limited to only the materials involved directly in a specific function, but not incorporating ancillary material use, or all stages of the life cycle, is of course the simplest. If a life cycle perspective is employed and multiple environmental impacts are included, then the assessment of material efficiency becomes closer to LCA with all the attendant richness and challenges. Put another way, the calculation of material efficiency is least complicated when constrained by a resolute ceteris paribus clause, holding all factors constant and changing only the quantity of a target material. This can be viewed as pursuing a strategy of Pareto improvement—no increase in material efficiency is deemed to have occurred unless all aspects of environmental performance either improve or remain unchanged. As the ceteris paribus clause is relaxed, the assessment increasingly looks similar to a LCA and analysis becomes more comprehensive but less novel with regard to current environmental discourse and assessment.

(c) From single materials to multi-material products

Material efficiency is a foundational principle of industrial ecology, which explicitly aims to decrease wastes and improve productivity and environmental performance in the use of resources; however, the industrial ecology research literature has struggled since its inception to separate material and product-based approaches. Jelinski et al. [32, p. 795] articulated the distinction at the seminal 1991 US National Academy of Engineering colloquium on industrial ecology:

The first [approach] is material-specific; that is, it selects a particular material or group of materials and analyzes the ways in which it flows through the industrial ecosystem. Such an analysis in manufacturing operations is generally made while products are in their manufacturing cycle, and any modifications to materials or processes tend to be costly and difficult. The second type of industrial ecology analysis is one which is product-specific; that is, it selects a particular product and analyzes the ways in which its different component materials flows may be modified or redirected in order to optimize product-environment interaction.

Yet, the distinction is difficult because the product life cycle starts with materials (in resource extraction and processing) which are then transformed into products in manufacturing and fabrication, and maintain their product character during use and reuse, but end again as materials in recycling and disposal (figure 2).

Extending mass-based material efficiency to multi-material products is not mathematically complicated. It can be done by simple weight-averaging each material component to arrive at a single measure of efficiency for the entire product. In LCA terminology, this is in effect mass-based allocation. It is much more complex to extend the concept of material efficiency to products where impacts other than mass are being considered, because the impacts related to the product as a whole (from the use phase, for example) must be allocated to its constituent materials. For example, consider a refrigerator that has three materials: steel, plastic and copper. It is straightforward to calculate the material efficiency of each constituent, say the amount of copper extracted in ore compared with the copper that is actually used to power a refrigerator with a given capacity. If the appliance uses five units of energy over a given period, the impacts from this energy use could be allocated to each material not only on a mass basis, but also using a cost basis, or a functional basis of some other kind. When this is done, the basis of calculating material efficiency is stripped of physical meaning, making the metric much less straightforward. Conversely, combining separate analyses of each constituent material into a single measure for the product as a whole also runs the risk of double-counting the product use phase impacts [34].

Figure 2 depicts the product life cycle of metal showing the transition from materials to products, as well as the subsequent transition from products back to materials in waste
management. Here, both materials and products coexist; some wastes are treated as materials while others continue to be viewed as products, which complicates the discussion of material efficiency. As the OECD [2, p. 18] notes:

...the production and use of materials and the subsequent generation of waste...are two sides of the same coin. They share many of the same driving forces—the materials we use and the resulting wastes are closely linked to how we produce and consume goods.

Recovery of secondary materials is a major recommendation to improve the environmental performance of industrial production, and this is appropriate when the original form of the material is largely preserved, as with office paper. When glued to a piece of plastic packaging and transformed into part of a multi-material product, this same paper becomes effectively unrecyclable and thus analysis in terms of material composition alone is misleading. Another important case is when multiple materials combine to create a product with distinct physical and chemical characteristics, as is commonly the case with chemicals and formulated products, and which again negates the possibility of recycling the constituent materials. Some materials are inefficiently produced from virgin materials but recycled quite efficiently, so this loss of a recycling route is a vital consideration.

5. Material efficiency, rebound and substitution

The discussion above describes various ways in which multiple materials and types of impacts can or must be incorporated into the assessment of the efficiency of materials. Recalling that the fundamental goal of material efficiency is to reduce the environmental impacts of material use, it is crucial that we also consider the economic consequences of efficiency measures and how these consequences might in turn affect the environment.
Several strategies for improving material efficiency hinge on the idea of reducing demand for primary (virgin) material, either through fulfilling demand using secondary material through reuse and remanufacturing, or by designing products to use less material overall. While these strategies can be quite effective, in this section, we explore possible unintended consequences of material efficiency in an economic context.

One economic effect of material efficiency measures that either reduce demand or increase supply is that they can also reduce the market price of a material. This can induce additional demand for that material, or for other forms of material consumption generally, through the rebound effect. The rebound effect relates to all types of efficiency improvements and has been most extensively studied with respect to energy [35,36]. For materials (as opposed to energy), the size of this rebound is generally only a fraction of the savings from material efficiency, but it is a useful consideration in striving for material efficiency in a multi-material world [37]. A metals example illustrates this point. Consider a single material with multiple end-uses, such as copper. Suppose that a new surface treatment on the inside of copper pipes allowed for the use of thinner sections, but without any cost reduction to consumers. There would be no consumer surplus to spend on other goods, and thus no rebound effect in this regard, but as piping is a significant end-use of copper, the overall market price may drop in the medium term, before primary producers have a chance to adjust output. This may increase the demand for additional copper piping in other regions of the world where the new type of pipes are not yet available, or it may increase the use of copper in a different end-use, such as architectural sheet.

These same issues become more complicated when choices among materials are involved in the design phase. If the goal is to reduce environmental impacts by using materials more efficiently, then inevitably the question arises: which material is most efficient for a given task? Considering thermodynamic material efficiency, it makes sense as a multi-material product designer to choose materials that are produced with energy efficiencies closest to the theoretical minima, or to concentrate research and investment into improving the efficiencies of the large volume industrial materials. There are two possible drawbacks with this approach. One concerns technological maturity, namely that some industrial processes are highly efficient because they have been under development for centuries. So choosing a thermodynamically efficient material may make sense in the short term, but ignores the technological potential for efficiency improvement in the long term. A second danger is that focusing on efficiency improvements for specific materials diverts attention from innovation around new materials, or new methods for delivering the same service. So for example, faced with approximately 180 million metric tonnes of steel entering the global transport sector (ca 2005) [38], one might invest in improving the environmental profile of transport by attempting to increase the efficiency of steel production. However, insofar as steel is one of the structural materials that is produced most efficiently in thermodynamic terms (and therefore harder to improve), it may be more useful overall to invest in efficiency improvements for aluminium engine blocks or composite structural panels that serve as replacements for steel.

A second example is more in line with our multi-material discussion. Major materials often compete in end-use sectors with other material substitutes. (There are many exceptions to this rule: modern structural concrete, for example, does not have a ready substitute in large infrastructure projects.) Based on the previous example, suppose design changes that improve end-use material efficiency in copper piping induce a reduction in market prices for primary copper. Where the use of copper is price elastic, for example, in high-tension electricity cables, power distribution companies may temporarily choose to run new lines using copper instead of aluminium, a more efficient metal on a mass basis.

Materials are not only linked economically through substitution in end-use sectors, they can also be linked technologically in their routes of production. Much of the world’s caustic soda (NaOH) is produced by the chlor-alkali industry, which has as a co-product a stoichiometrically equivalent amount of chlorine gas. This means that efforts which increase the end-use efficiency of chlorine alone may not actually decrease the amount that is produced, as supplies can be driven by the higher price of NaOH. Such production interlinkages are particularly relevant...
for petrochemicals, where a single distillation column might produce a dozen distinct materials, and for metals, where a significant number of elements occur only as contaminants or ‘daughter materials’ in other ores [39,40].

6. The political context of material efficiency

The efficiency of materials can change as politics and public policy alter costs, limit access to resources, internalize externalities, or otherwise change the biophysical context in which materials are obtained and used. If, for example, safety regulations alter the structural requirements in automobiles, the materials used can, not surprisingly, change as well. More subtly, politics and policy are the platform for arguments about which materials are efficient or most efficient. As society pursues sustainability, material choice becomes one avenue for the pursuit of such goals. This has impacts on firms involved in resource extraction, material processing and related commercial activities, potentially increasing or decreasing market share or even altering market access.

Environmental competition among materials based on mass has occurred in the packaging industry where the quantity of material used is sometimes the basis or key component of judgements about environmental preferability. This is because much of the discussion regarding the environmental impacts of packaging has centred on post-consumer waste where weight is the typical metric. Debates about the relative impacts of plastic, glass, metals and paper packaging are legion and date back many decades [42]. When measures based on weight (or other environmental attributes such as recyclability) disadvantage a particular interest, it is common for that interest to reframe the debate by emphasizing other environmental attributes [43]. Such reframing is one of the motivations for the development of LCA in the 1960s. Here the political and policy discourse mirrors the broadening of the criteria for material efficiency described above.

When material efficiency evolves into environmentally calibrated material efficiency, the contestability of LCA findings assumes a central role. LCAs are contestable because newer or better data can always be sought, because the choice of system boundaries has a critical impact on the results, and because various elements of the methodology are inherently value-based. The contestability of what is deemed environmentally preferable—or in this context efficient—intersects crucially with the politics of material competition. The absence of a uniquely correct technical answer to what is efficient facilitates ongoing political contention. The examples are legion ranging from the iconic ‘paper versus plastic’ dispute over shopping bags [44], to steel versus aluminium in automobiles, to concrete versus asphalt in pavement [49,50].

7. Final comments

The analysis presented in this article suggests that, because the ultimate goal of material efficiency is to reduce the environmental impacts associated with material use, material efficiency strategies based solely on mass should be integrated with other strategies that explicitly consider impacts. To return to the premises outlined at the beginning of the article, this does not mean that unexploited and potentially significant opportunities do not exist, or that it is old wine in new bottles. Rather the analysis raises the question of whether the pursuit of material efficiency can sidestep the complicated challenges already confronting environmental researchers and decision-makers when they engage in LCA or product-based approaches.

7 While a fuel rather than a material, corn ethanol provides an excellent example of how environmental criteria can constrain market access. The California Low Carbon Fuel Standard (LCFS) established in 2007 required that fuels sold in the state meet targets for greenhouse gas emissions (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). Corn ethanol producers worried that their product would not meet the LCFS requirements, thereby blocking access to an important market.

8 For just one example, see a study commissioned by the Council for Solid Waste Solutions, an organization representing the US plastics industry [41].

9 References to some of the competing studies can be found in work by Kim et al. [45,46]. An informal account of the battles between the steel and aluminium industries can be found in two short articles by Reisman [47,48].
Given the complexities and difficulties, both conceptual and mathematical, in using the analytical framework of material efficiency in a multi-material world outlined in this article, what can industrial designers, planners, policy-makers and others do? We conclude with some final comments and practical recommendations based on the concept of scale. Decisions made at the consumer level or the individual project level are likely to have relatively small-scale consequences, for the individual or for a limited supply chain. If we have reasonable confidence that material efficiency correlates with overall environmental improvement more often than not, it may be completely appropriate to base decisions on mass-based material efficiency, for the design of a small bridge, for example. Using less steel or concrete translates into cost savings and a reduction in environmental burdens associated with materials production, but the particulars of the design in no way affect macro-level material production, pricing or economic structure. Modelling the indirect consequences of multi-material decisions is not straightforward, and most small projects (and especially individual consumers) have neither the time nor the resources available to realistically address these considerations. Put in a more circumspect way, failure to grapple with the full and complex suite of issues is less likely to engender perverse outcomes of significance. On the other hand, decisions with large-scale material and market consequences can and should expand the notion of material efficiency to include multiple impacts, interlinked production of materials, economic effects and political consequences. Changes to government procurement, national building codes or regulatory limits for example may alter prices and cause changes in production locations, technologies or the entire economic structure of an industry. This is the scale at which material efficiency should be applied carefully, to ensure that environmental goals can be met without unintended consequences. It is also usually the case that decision-makers at this level have access to the financial and technical resources (and often the legal imperative) to carry out comprehensive analyses.

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