Manufacturing and the Science of Sustainability

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Abstract

A new area, called Sustainability Science, is engaging large system scientists to address the challenges that face the future of human society on planet earth. In this paper, the methods and frameworks of diverse disciplines are reviewed and compared with those of the manufacturing community. The results show significant differences between disciplines, including the level of urgency expressed. Synthesizing these divergent viewpoints, this paper makes suggestions for needed research on “sustainable manufacturing”. The main message is that manufacturing needs to significantly increase the boundaries of its analysis to be able to understand its effect at the global scale.

Keywords:

Weak Sustainability; Genuine Investment; Eco-Systems Ecology; Panarchy; Resource Accounting; Triple Bottom Line; Scale; Human Well-Being

1 INTRODUCTION

Recent papers have identified an emerging area of research called sustainability science. This new area of study looks at the complex interactions between the methods of society and eco-system services and human well-being, over long time scales and at global dimensions. The earliest manifestations of this new science involve the natural sciences (biology, ecology, etc.) on the one hand, and the social sciences (sociology, economics etc.) on the other, with systems modelers of many persuasions in the middle [1], [2], [3], [4]. Manufacturing, as one of the major sub-systems that connects eco-systems services to human well-being has an important role to play in this new emerging field [5],[6], [7], [8]. In this paper, we review various approaches to understanding the concept of sustainability and compare them to sustainability initiatives in the manufacturing sector.

2 ALTERNATIVE VIEWS OF SUSTAINABILITY

A major thesis of this paper is that until there is reasonable agreement on a working idea of what sustainability means, it will be difficult or impossible to measure progress or describe a way forward. In this section, brief summaries of alternative views of the concept of sustainability within recognized scientific disciplines are offered. The reviews include; 1) economics, 2) eco-system ecology/resilience, 3) resource accounting, and 4) the business approach called the triple bottom line (TBL).

2.1 Economics

Starting from the concept of sustainability as defined in the UN document “Our Common Future” [9], economists in collaboration with ecologist have put forth an operational scheme for estimating society’s sustainability [10]. In this paper, sustainability is defined as the requirement that our so-called inter-temporal social welfare must not decrease over time. The inter-temporal social welfare is calculated as the present discounted value of the flow of utility from consumption from the present to infinity. Under certain conditions, this is equivalent to the more transparent requirement that *genuine wealth per capita* must not decline. Hence the change in genuine wealth, called *genuine investment*, must be equal to or greater than zero. Genuine investment is the sum of the values of all capital stocks including *manufactured capital, human capital and natural capital*. The accounting is done in dollars which means that economic equivalents of these different types of capital must be obtained. The difficulties in establishing prices for components of natural capital are acknowledged, and a representative calculation is made for countries, regions, similar economic groups, and the world, and announced yearly in the World Bank’s publication The Little Green Data Book. Figure 1 gives the recent accounting for the World [11]. The results (given in percent of gross national income – GNI) indicate that the world’s manufactured capital assets grew at 7.9 %, the human capital assets (represented by education expenditures) grew at 4.2 % and the natural capital assets declined at 5.0 %. The result is greater than zero (+7.2 %; note the rounding error) and so by this calculation the world is sustainable.

World

Population (millions) **6,697** Land area (1,000 sq. km) **129,611** GDP ($ billions) **61,063.3**

National accounting aggregates	
Gross savings (% of GNI)	20.9
Consumption of fixed capital (% of GNI)	13.0
Education expenditure (% of GNI)	4.2
Energy depletion (% of GNI)	3.9
Mineral depletion (% of GNI)	0.5
Net forest depletion (% of GNI)	0.0
CO_2 damage (% of GNI)	0.4
Particulate emissions damage (% of GNI)	0.2
Adjusted net savings (% of GNI)	7.2

Figure 1: Results from the 2010 Little Green Data Book produced by the World Bank indicate a positive genuine investment.

This is the so-called *weak form of sustainability* which allows substitution between capital stocks. In other words, depletions in natural stocks can be compensated by additions to manufactured and human capital stocks. Substitutability, and its implied value

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system and technical feasibility, is an issue for any aggregate measure of resources, and is not unique to economics. Economics, however, seems to take it to the farthest extreme by allowing for the compensation of lost eco-system services, with human engineered products and institutions. This is not only an extremely optimistic statement about human abilities, but also implies a vision of the future without nature, or at least with much less natural capital than we now enjoy.

Because many people are uncomfortable with this vision and because the technical feasibility of substituting for ecosystem services on a global scale is in doubt, many people criticize the weak form of sustainability. See for example Daly and Daly and Farley [12], [13]. At the same time, the idea to aggregate resources in an attempt to measure some aspect of sustainability seems potentially worthwhile, and should be further explored [14]. In fact, the economists carry this approach much further than outlined here, by attempting to include the contributions to our economic productive base provided by human institutions [10]. See Dasgupta for a short, concise description of this calculation [15], and for more detail see [10], [16].

2.2 Ecosystems Ecology

Ecosystems ecology brings a very different perspective to the issue of sustainability, one that may not be familiar to manufacturing engineers. Overall, ecosystem ecologists do not see sustainability as an equilibrium state, but rather as a process that naturally includes phases of decline and recovery. The central question is, can the system accommodate change and still retain controls on function and structure [17]. This inquiry is closely aligned with the new study of resalience, see for example the website for the resalience alliance [18]. A cornerstone of this effort is a systems dynamic conceptualization called *panarchy* [19]. Panarchy is a stylized representation of the dynamics of an adaptive system based upon observations from ecosystems ecology. It is hypothesized that other adaptive systems (including ecological, social and economic systems) may go through similar transitions. It places a useful emphasis on dynamics and transitions, identifying four crucial stages in the prototypical transition: 1) growth, 2) conservation, 3) release, and 4) reorganization. The scheme is shown graphically in Figure 2. The authors identify two meta-parameters that can indicate where one is in this scheme; "potential" equivalent to the "y" axis in Figure 2, and "connectedness" equivalent to the "x" axis. A third variable, out of the plane of Figure 2 (the "z" axis) is "resilience". If a system is not resilient it may move off of the pattern shown in the figure to a new pattern or to a dead end or "trap". The researchers have identified two important traps. One is the so called "Rigidity Trap". As described by Gunderson and Hollings, "Rigidity traps occur in social-ecological systems when institutions become highly connected, self-reinforcing and inflexible". The other is the so called "Poverty trap". As described in the resilience literature, "this is a situation in which connectedness and resilience are low and the potential for change is not realized" [19]. Ecosystem ecologists offer many examples of these behaviors in nature and speculate on the application of this framework to other systems. For example, in Gunderson and Holling, a testable hypothesis is proposed for applying the panarchy framework to industrial systems, for example the Bell telephone Co. in the U.S. For those who study business cycles, there seems to be some similarity with concepts such as the Kondratiev long wave, see [20], [5]. Overall the resilience literature is highly integrative bringing together scientists from different fields of study. Much of the earlier work however is mostly conceptual, such as the panarchy framework. A recent paper identifies specific global limits for several ecological problems described in the next section [21].

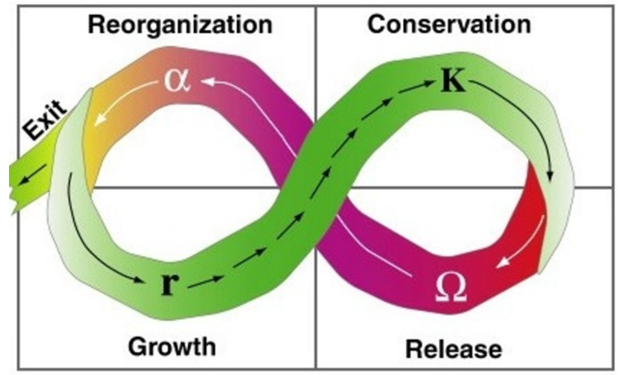


Figure 2: Graphic representation of an adaptive cycle for a complex system.

2.3 Resource Accounting

Resource accounting is the physical equivalent of the economics approach to counting identified resources needed to maintain some aspect of sustainability. The accounting is done in physical units, rather than monetary units, and usually employs some version of a "sources" and "sinks" view of the planet. That is, human activities interact with the planet by extracting energy resources, materials, biological entities and other sources, process them, and then deposit the residuals back to the planet that acts as a sink capable of absorbing a certain amount of these wastes. This approach may be done with varying degrees of rigor depending largely on how well the system is defined and the tools employed. Thermodynamics would be among the most rigorous physical accounting approaches [22], [23], [24], [25]. While using physical units greatly limits the degree of aggregation one can usefully accomplish, large categories of natural capital type resources are commonly counted. Prominent examples include: Primary energy resources measured in units of energy; climate change gases, measured in CO_2 equivalents; water use measured in weight or volume; acidification potential measured in hydrogen ion equivalents; material resources measured in weight, and biological extinction measured in rates of species loss.

In fact, all scientific investigations of sustainability ultimately resort to some form of resource accounting to state a problem or measure progress. And it is the resource accounting arguments which ultimately make the strongest and clearest statements concerning the current unsustainable practices of humanity. Examples of unsustainable trends come from a variety of sources, of particular importance are the effects on global eco-system services addressed in the International Panel on Climate Change [26], and the Millennium Ecosystems Assessment [27], [28]. These reports and others point to a broad array of disturbing and potentially disastrous trends including climate change, ocean acidification, nitrogen and phosphorous overloading, freshwater depletion, biodiversity loss and land system change. See also [21].

The most notable features of the resource accounting approach are; 1) that attention is directed predominantly to the natural environment, and 2) that much of the news is quite concerning if not alarming. This contrasts starkly with the much more optimistic view given by Arrow et al [10] and the seemingly non-committal view of Gunderson and Hollings [19]. In particular, an optimistic case can be made that humans can employ forward looking mechanisms and institutions to anticipate potential future disruptions, and plan accordingly [19]. At the same time, humans can game these very same mechanisms (as the recent financial crisis clearly illustrates) and fail to perceive potential precipitous decline. This potential inability to adapt would be an example of the so-called "Rigidity Trap" described by Carpenter and Brock [17] and others.

2.4 Triple Bottom Line

The triple bottom line is a business response to the need for corporate performance measures that go beyond shareholder value, and include social responsibility and sustainability. The term is generally attributed to John Elkington writing in the California Business Review in 1994. Triple Bottom Line accounting includes not only corporate financial performance, but also an evaluation of potential impacts on people and planet. While it may appear to include some of the same topics as in the genuine wealth calculation mentioned earlier, the focus is on the firm and the accounting has not been standardized. In practice, it is more a portfolio approach, where the different spheres of activities are treated separately. While this method is indeed a step forward in terms of corporate acknowledgement of social and environmental issues, it is clearly a work in progress and whether it could actually have an impact on sustainability needs to be tested. The main problems are that the accounting is limited in scale, the methods may not be fully disclosed, and business as usual can often be dressed up to look like a new contribution to sustainability. Later examples will show this explicitly.

2.5 Summary

This brief synopsis of alternative views of sustainability is offered to illustrate the range of views on this topic and the uncertainty that faces the development of a science of sustainability. It seems that in a situation where we would all want clarity, it is not to be had. The problem resides not only in the vast complexity of the global environmental-social-economic system, and the weakness of the "unsustainable signal" as experienced by the average inhabitant of the planet, but also in the hugely ambitious agenda contained in the simple word "sustainable". Even some of the most fundamental concepts are seen quite differently by the various disciplines engaged in this study. For example, consider the test question, would the addition of many more people to the planet improve or decrease the sustainability of human society? Those who see resources as limited will divide finite resources by a growing population and tend to answer in the negative. However a subset may say the opposite. The difference depends on whether one sees additional people as a potential resource, or primarily as consumers of the resources. An interesting contribution in this area is offered by the Harvard economist Michael Kremer who has shown that the rate of technological progress correlates very closely with population levels [29]. That is, the more people there are, the more new ideas and opportunities for development, and so the more we advance. This view is discussed in a popular book by Harford [30] to illustrate how contradictory the solution to sustainability might be. However to many, this view seems to deny any biophysical limits to growth. In fact, it may sound like a Malthusian mistake with the opposite sign. Indeed, those who come to this problem from a natural resource accounting point of view, would probably cast humans first in the role of consumers, and secondly as those who could modify the consumption process. The alternative views presented here are in stark contrast.

This result, that even a most basic question, such as the role of human beings in sustainability, has no simple uncontestable answer, is not unique. Other basic questions, often the foundation for action plans in "sustainable manufacturing" are equally complex. The result is this; there is plenty to study concerning manufacturing and the science of sustainability and the sooner these produce results, the sooner manufacturing will be able to clearly address the problem.

3 THREE QUESTIONS ON SUSTAINABLE INDUSTRIAL PRACTICES

Here we propose three questions concerning sustainable behaviors. The questions are intended to expose the limitations of simple notions concerning sustainability.

Gulf Oil Spill in the U.S.

A simple question might be to ask how would one evaluate the performance of the company BP during the recent oil spill in the Gulf of Mexico? Indeed by any measure this was a lose-lose-lose proposition. The company lost economically, the environment lost (although we do not know the extent of the damage yet) and indeed many local people lost by losing income and potentially their livelihood, and having their environment damaged. This was the largest oil spill in U.S. history, and at about 200 million gallons likely the largest of its kind in world history. At the same time BP has been known for promoting renewal technologies and providing investment funds for many of these. Also some may have seen BP's response as proactive. So how would you rate BP's behavior? Are they sustainable?

The easy answer to this question is "no", but as this paper is being written the investigations into the roles of the various players is currently in progress, and the extent of the ecological damages may take years to understand. Hence, in this case we may look to the bigger picture proposed by both the ecosystem ecologist and the economists and ask a larger question - not how did BP perform, but how did (or will) the overall system perform? The answer to this question may lie more in how the institutions which control deep water drilling and are charged with guarding ecosystems, while at the same time providing energy resources, respond to this disaster. Similarly we may ask the question how do the consumers, who ultimately drive the need for deep water drilling, respond? Are they aware of the consequences of their actions or is the signal too weak to produce a response? We leave the question unanswered but use it as an example of how we have to expand our analysis framework to get ultimate answers to these questions.

Solid State of Lighting

Consider the question – should an improvement in the energy efficiency of lighting be considered a engineering contribution to sustainability? This topic is currently of great interest because of significant new improvements to solid state lighting and recent studies concerning the life cycle energy use of solid state lighting [31], [32]. Anyone who owns an LED flashlight already knows that this form of lighting is very efficient because the batteries last for a very long time. However, it is also true that solid state devices are made by semi-conductor type manufacturing process which can be very energy intensive. So the question is, when viewed over the product life cycle i.e. manufacturing and use, is solid state lighting more efficient than incandescent and/or florescent lighting? Recent LCA studies indicate that the answer to this question is yes, the solid state devices can provide an equivalent amount of illumination for a much smaller amount of energy – something like 3 to 5 times less energy depending upon the exact nature of the comparison [31]. This would seem then, one face value, to be a very significant improvement and certainly a candidate for being called a contribution to sustainability.

But there is more to this story. A further study of this issue looked more into the nature of our demand for lighting, and explores the question – "just exactly how much lighting do we want?" That is, will we be happy with what we got, and continue to use the same amount of illumination and therefore save energy with solid state lighting, or will we take advantage of this efficiency improvement and actually increase our amount of illumination and thereby potentially offset some or all of our expected savings? [33]. This is the kind of question that economists can address, using economic growth models and other models to connect our demand for illumination to other factors. As it turns out, the result to our question can be surmised roughly from available empirical data. That is, observations from over 300 years, for various geographic units, indicate that the demand for lighting per capita, ϕ, is directly proportional to per capita gross domestic product (gdp) divided by the cost of lighting CoL [33], as given in equation 1.

$$\phi \sim \frac{gdp}{CoL} \tag{1}$$

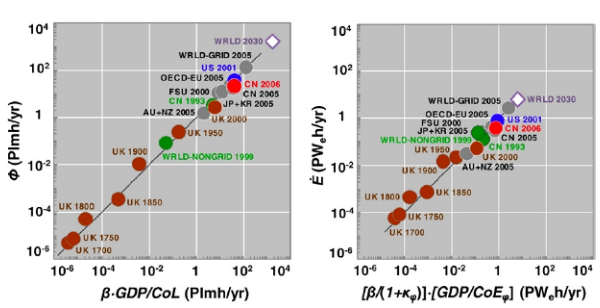
This result, and one that can be derived from it, giving the total power used on lighting, are shown in Figure 3 [33]. The data show two things; 1) the wealthier we are, the more lighting we want, and 2) the lower the cost of lighting, the more lighting we want. Most notably, the graph shows no sign of saturation. We may saturate in the future, but that is a debatable point (and one that is discussed further in the reference [33]). The evidence so far however is not good for energy savings, and in fact the paper (using a more complex economic argument) predicts more energy use with solid state lighting not less.

Efficiency data from an earlier paper puts this into perspective. Figure 4 shows historical improvements in the efficiency for two technologies: steam engines and lamps plotted on a "linearized" logistics curve [34]. Here we are interested in lamps. Current solid state lighting would appear roughly in the upper right hand corner of the figure. What becomes apparent from this figure is that while solid state lighting indeed represents a significant improvement in the energy efficiency of lighting, it is not, from a historical perspective, unique. That is, going from paraffin candles to Edition's first lamp, or from tungsten filament incandescent lamps to sodium vapor lamps where also significant improvements in there own right.

We return then to our original question, should an improvement in the energy efficiency of lighting be considered an engineering contribution to sustainability? Or does it look remarkably like business as usual? This seems as a core question for those who want to study manufacturing and sustainability.

Remanufacturing and Energy

The third question is, does remanufacturing save energy? In many references one can find comments that remanufacturing is the best option for end-of-life product. The obvious benefits are that remanufacturing can generally save some (usually large) portion of the invested energy used in both the materials production as well as the manufacturing. (The assumption is usually made that the



(a) (b)

Figure 3: a) Empirical data showing the correlation between illumination and GDP divided by the cost of lighting

b) Converts the data to show energy usage by illumination see [Tsao 2010].

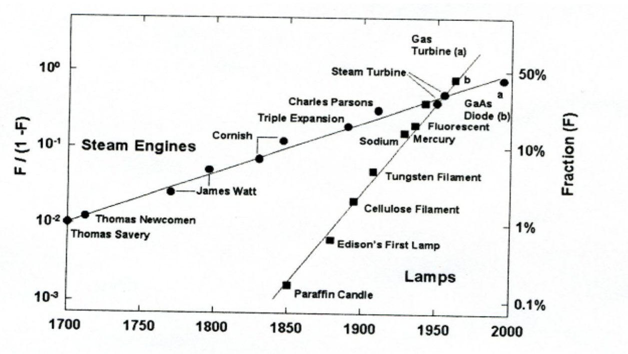


Figure 4: Historical efficiency data for steam engines and lamps from Ausubel and Marchetti 1997.

remanufactured product is a substitute for a new product.) But a recent study of remanufacturing of eight different products reveals that energy saving may not always be in favor of remanufacturing [35]. The result depends heavily on whether the product has an energy intensive use phase. That is, if the product has a power cord or an internal combustion engine attached to it, then the use phase of the life cycle will very likely dominate the energy use. Since it is a major product design trend to power-up previously "passive" products, the use phase is coming to dominate energy use for many products. Furthermore, since the first powered design will likely be inefficient, the ironic implication is that future energy efficiency improvements in the design could act to undermine remanufacturing. The study found that in 25 case studies, 8 showed clear energy savings for remanufacturing, 6 showed clear energy savings for buying new, and 11 cases were too close to call. The results depended heavily upon use phase energy efficiency trends and could change dramatically with time. For example, while it made sense from an energy savings point of view, to replace a damaged compressor and extend the life of a refrigerator in the 1960's, in the 1990's it was better to buy a new refrigerator. Ultimately however, if products can move asymptotically to a steady highly efficient state, the case where remanufacturing saves energy could be restored. It remains to be seen if such a scenario obtains.

4 RESEARCH QUESTIONS

A review of the sustainability science literature shows considerable uncertainty in regards to a definition of sustainability, disagreement concerning the roles of major players in this problem, and the lack of a clear path forward. This contrasts sharply with many of the ideas put forth as "sustainable manufacturing". These are primarily programs of self improvement (and to some extent self preservation) and technology development to address market opportunities. They appear to be based upon a much clearer vision of the mission, usually involving resource accounting arguments, (but addressed at a relatively small scale). A resource accounting framework provides a clearer enunciation of the problems, and a basis for measurement and hypothesis testing. At the same time however, it must be recognized that even if one accepts the resource accounting approach, this must be woven into a larger picture that addresses how these resource depletions at various scales might interact and ultimately how they provide for human needs. Furthermore one must study the problem at a sufficient scale so that actions at the manufacturing level can be followed to higher levels, ultimately to a global scale. One can even go farther in the analysis to anticipate the temporal pattern of these actions. It appears that even when we do good, the scale of our actions can lead to new effects not anticipated. For example, consider the substitution of MTBE for TEL, and HCFC's for CFC's. In each case an improvement on a unit basis is accompanied by an expansion in use, and a realization of yet new problems. Note that at the time of its introduction, CFC's could have been easily characterized as "green", an improvement, or even "sustainable". See Allenby's comments in [36]. The problem is that the scale of human activity is so large that whatever we do it will affect the environment. The study of sustainable manufacturing needs to reorient itself so that this concept is at the center of the discussion.

Several critical areas for sustainable manufacturing research are identified below.

1. Scale – Manufacturing must expand the boundaries of analysis if it wants to understand its impact on sustainability. This does not mean just to distant components of manufacturing, but also to social and environmental effects. There are indeed many dimensions to this expansion, several of them are mentioned in the following points. See [37], [38], [39].

2.Measuring Human Well-Being – The ultimate goal of sustainability is to maintain some level of human well being extending indefinitely into the future. While human well being is admittedly a complex topic, there are many credible studies that have explored this topic and proposed various measures. Examples range from the happiness index to the GINI coefficient of inequality, to the UN's human development index (HDI), the index for sustainable economic welfare (ISEW) and the genuine progress indicator (GPI) [39], [16], [40], [41], [42] [43]. Additionally, some researchers are working on the development of a so-called Social Life Cycle Assessment [44]. While each of these can be challenged in some way, they all appear to offer more or additional sensitivity to the human condition compared to the usual default measure, which is the per capita gross domestic product (GDP) or some similar financial measure. In fact many of these human well being indicators show that while per capital GDP may be rising in many developed countries, measures of human well being are staying flat or even declining. These measures should be central to the sustainability discussion and need further and vigorous development. Even in their current state of development, application of these measures to the stake holders involved in manufacturing's actions would be enlightening. The results should show both the benefits and disadvantages of manufacturing. Furthermore, they may provide important insights that would allow one to differentiate between various manufacturing activities. Given the global nature of manufacturing, one would have to address how these large geographical boundaries would be treated.

3. Measuring Resources – Resource Accounting is based upon the widely held premise that there are certain types of resources that need to be maintained in order to provide for the sustainable development of human society. These identified resources generally correspond to certain natural capital stocks and eco-system services or the accounting is done on the anthropogenic emissions or actions that degrade and threaten these services. While sustainability issues can exist at all scales for society, primary concern must be focused on those problems that exist at the global scale. Several publications attempt to list these major global scale challenges. See [45], and [21].

Resource accounting approaches can use alternative accounting schemes. Two extreme cases would be highly aggregated measures (such as the genuine investment accounting scheme of the economists) or by considering individual levels of specific resources and emissions. Both methods have advantages and disadvantages. When using highly aggregated methods, one would need to acknowledge potential interactions or stay away from these in the accounting scheme. Highly aggregated measures would have significant advantage in modeling and developing conceptual frameworks for future evolutionary paths of society. On the other hand, identifying specific resource issues allows for a much more in depth analysis. These could address in greater detail potential limits of the global system and complex interactions between the various dimensions of the problem.

In the aggregate resource accounting method, the issue of substitutability would need to be addressed in some detail. Note that the application of the genuine wealth calculation or some variation on this theme to manufacturing could result in the differentiation between the benefits provided to society by different products, for example infrastructure products versus consumer goods. While this is a very value laden issue, there is wide agreement in the psychological literature that all needs are not equal. That is, one could attempt to link product, to need, to sustainability. For engineers a particular attractive aggregate accounting scheme could be based upon the consequences of the second law of thermodynamics. These would include estimating exergy losses and entropy production at the global scale. See [22], [46], [24], [25], [23].

Concerning accounting schemes that address individual global scale problems, a recent paper by Rockstrom et al identifies 9 potential problems and makes a first estimate of quantified global limits for seven of them. That list includes; 1) climate change, 2) ocean acidification, 3) ozone depletion, 4) nitrogen and phosphorus cycle overloading, 5) global fresh water withdrawals, 6) land system change, 7) biological diversity, 8) atmospheric aerosol loading, and 9) chemical pollution. The paper claims that three of these, climate change, nitrogen and phosphorus cycles overloading and biological diversity, have already transgressed the safe operating space for the global environment. The obvious challenge for manufacturing is to connect their effects on these problems from the manufacturing scale to the global scale.

4. Mechanisms of Interdisciplinary Study – Increasing the scale of analysis will inevitably involve crossing interdisciplinary boundaries. How to do this gracefully and rigorously is an important challenge. In the review of sustainability science literature it seems that the ecologist and economists have started the process of successful interdisciplinary studies. This issue strongly affects the professional development of young academics.

5. Subdivisions by Topic Area – Several major themes emerge that both span the breath of the sustainability research area, but at the same time provide a focus which allows measurement and modeling. These area include:

4.1 Energy resource use and efficiency

The effect of energy efficiency on conservation and growth has been discussed since at least 1865 when Stanley Jevons published his book on coal. Since then it has been measured (the direct rebound effect), analyzed and debated primarily in the economics literature, and proposed as the driver of economic growth by Ayres. See [47], [48], [49], [50], [51]. This topic is among the most important that needs to be understood. Proposals to increase energy efficiency without an understanding about how society would use those advances could lead to surprisingly different results than expected, as illustrated in the earlier sections in this paper.

4.2 Materials use and efficiency

Materials connect manufacturing to the environment both as a source of raw materials and as a sink for the residues. And materials connect manufacturing to people by providing for their needs and quality of life. Current trends show a growing need for more materials as the world develops, the use of more elements in the periodic table (leading to complex mixtures) and increased needs for higher purity materials. Furthermore, materials are energy intensive and newer materials generally have even higher energy requirements. While the materials with the largest use have been around for some time leaving only finite opportunities for energy and CO_2 efficiency improvements, newer materials may present major opportunities. How materials are used, substituted and recycled is central to sustainable manufacturing. From the manufacturers point of view: how will materials use in future products be affected in light of potential restrictions, reporting requirements and standards, constrained supplies, fluctuations, and potential increases in prices and recycled content? See [52], [53], [54], [55].

4.3 Geography and supply chains

The spatial arrangement of supply and demand presents a challenging and as yet largely unexplored area for sustainability research. In a recent book David Mackay analyzes the energy needs and the renewal energy resource potentials for England and comes to the conclusion that it cannot supply its own needs [56]. It must be engaged in some kind of trade to do so. This is a sobering and useful conclusion that highlights the problem; what does a sustainable world look like? Who trades with whom and for what reasons? For example, a recent study suggests that if the price for carbon goes to $100/tonne CO2, laptop and notebook computer manufacturing for the U.S. market should move back from China to the U.S. [57]. From the manufacturers point of view, how will supply chains be affected in terms of changing labor rates, shifting markets, materials availability and centers of manufacturing, and potentially increasing energy prices and carbon taxes imperfectly applied in different countries across the world?

4.4 Measurements, Metrics and Tools

The measurement of anthropogenic outputs and ecological and social responses are an area of considerable potential for sustainable manufacturing. Manufacturing engineers can develop these and this activity does not necessarily depend directly upon the definition of sustainability. Further manufacturing can contribute to the analysis of the data, and interpretation and use of it in models. While it is rewarding to see that LCA has grown in application, many tough problems remain concerning allocation, boundaries standardization and accuracy. At the same time tools that move beyond single product evaluations are a critical need for manufacturing. Indeed many modeling problems exist at many levels.

4.5 Technology development, business practices and innovation

Many people are banking on innovating our way out of the sustainability problem. This is a major paradigm for technology optimists. Given that we have only first begun this journey, as we focus our attention many new developments can be expected. Skeptics on the other hand will counter that new technologies have never really been evaluated from a global perspective before. The game is changing, and the hurdles to success may be much higher. New technology needs to be encouraged and guided by informed social and environmental analysis. For manufactures this will be similar to concurrent engineering and the quality movement. We must move away from pampered products that only perform well in a highly constrained environment. There will be many new opportunities here for manufacturing.

The bottom line is that to connect manufacturing to the new Science of Sustainability, much larger boundaries of analysis need to be considered. While an evaluation at the level of the firm is a desirable goal, without a credible framework that connects the firm to the planet the local evaluation risks being meaningless.

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