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A systems and thermodynamics perspective on technology in the circular economy

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Abstract
Several discourses on environment and sustainability are characterised by a strong confidence in the potential of technology to address, if not solve, the ecological impacts resulting from physically expanding systems of production and consumption. The optimism is further encouraged by leading environmental engineering concepts, including cradle-to-cradle and industrial ecology, as well as broader frameworks, such as natural capitalism and the circular economy. This paper explores the viability of their promise from a biophysical perspective, which is based on insights from system dynamics and thermodynamics. Such an ecological reality check is generally ignored or underestimated in the literature on aforementioned concepts and frameworks. The paper ultimately reflects on what role society can realistically assign to technology for resolving its ecological concerns. While environmental engineering undoubtedly has something to offer, it will end up chasing its tail if the social and economic forces driving up production and consumption are not addressed.

Keywords cradle-to-cradle, industrial ecology, circular economy, system dynamics, thermodynamics

1. Introduction

To manufacture complex infrastructures, products and services, engineering relies on inflows of natural resources from the planet’s natural system in the form of energy and matter. The process also returns outflows of waste and emissions. Historical periods of economic activity have intensified these flows and their associated environmental impacts. Technology has played both aggravating and mitigating roles in the process.

Environmental engineering emerged in attempts to reduce the flows or their negative (side-) effects. Roughly until the first half of the 20th century, early environmental engineers assumed that the solution to pollution was dilution and dispersion. With the proliferation of industrial and consumer goods and the emergence of new forms of chemical waste, end-of-pipe solutions appeared after World War II, followed by pollution prevention strategies at the source. Engineers developed techniques for waste minimisation and recycling, as well as for improving resource efficiencies. These strategies were then integrated in the concept of cleaner production in the early 1990s. More recently, although largely based on older principles, several practices and concepts with strong engineering content claim to address the environmental impacts of industrial production and consumption without threatening economic expansion. These include cradle-to-cradle (McDonough and Braungart 2002; McDonough et al. 2003), industrial ecology (Frosch and Gallopoulos 1989; Graedel and Allenby 1995), natural capitalism (Hawken et al. 1999; Lovins et al. 1999) and the circular economy (Ellen MacArthur Foundation 2013). Other related concepts and designations include sustainable design, radical resource productivity, bio-mimicry, by-product synergy, technological food webs, industrial symbiosis and many more. Despite the changing terminology, the basic principles remain the same.

Common to these concepts is the belief that with the right innovations economic growth and environmental safekeeping can be complementary rather than in conflict. To explore the viability of this expectation, the global industrial machine must first be seen as a subset of a larger natural system, i.e. an ecological envelope (Boulding 1966). This envelope imposes several biophysical limits to human production and consumption. The combined insights from system dynamics (Meadows and Wright 2008) and thermodynamics (Corning 2002) will be used in this paper to examine some of these limits and to provide a reality check for aforementioned engineering concepts and frameworks. The paper's broader questions are about the role that we can realistically assign to engineering and about the point when we need to turn towards more fundamental social and economic transformations.

2. Understanding biophysical limits

The fields of system dynamics and thermodynamics provide valuable contributions to our understanding of biophysical limits, both quantitatively and qualitatively.

2.1 System dynamics

System dynamics tells us that a physically growing system dominated by reinforcing feedback[1] will eventually run into some kind of physical constraint, in the form of balancing feedback. In a growth-based industrial system, the more factories are operating, the more goods and services are produced and consumed. The resulting increase in profits leads to investments in new factories. Such a physically growing system relies on increasing inflows and outflows of energy and matter. In a bounded natural environment, whether balancing feedback originates from a non-renewable or a renewable resource makes a difference in how growth is likely to end, but not *whether* growth will end (Meadows et al. 1972; Turner 2008). We will now briefly explore both scenarios.

When an oil industry exploits a new oil field, profits are partly invested in establishing additional oilrigs, which leads to more oil extraction, higher profits and further investment in oilrigs. This represents reinforcing feedback. However, operations will first pick the proverbial low-hanging fruits. At some point, the extraction costs will outweigh the benefits and the resulting lower profits will reduce investments in new oilrigs. This represents balancing feedback. On the other hand, as oil becomes scarcer, prices go up and more money can be invested in new oilrigs, which pushes extraction upward. One feedback loop might dominate for a certain period of time and drive the system in a certain direction, but this doesn't mean that the other feedback loops have stopped existing. Meadows and Wright (2008) show that the potential lifetime of a newly discovered oil field available under the initial scale of operations is considerably reduced as a result of the dynamics at play.

A question to ask is: what if capital becomes more efficient instead of larger? Instead of expanding into new oil fields with additional oilrigs, more precise technology can be applied—for example through enhanced oil recovery techniques, such as gas or chemical injection. This can prolong extraction for a little while longer, but the upshot is a faster depletion of oil

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[1] Systems can be understood in terms of stocks, flows and feedback. Stocks are accumulations of things (not necessarily physical) that change over time through the actions of inflows and outflows. Feedback occurs when changes in the size or composition of a stock affect the rates of inflow and/or outflow. Feedback is balancing or reinforcing, i.e. negative or positive.

towards the end (Meadows and Wright 2008). This indicates a fundamental role of technology in relation to ecology. It can act as a catalyst that speeds up the process of depletion of non-renewable resources.

We cannot engineer away the confines of a non-renewable stock of oil, coal, gas, iron, aluminium, copper, uranium or certain groundwater aquifers. What if we were to switch entirely to renewable natural resources?

Non-living renewables (sunlight, wind or rivers) regenerate through a steady input that keeps refilling the resource stock. Living renewables regenerate through reinforcing feedback: more fish means more reproduction and therefore more fish, for example. Another reinforcing feedback loop occurs when an increase in number of boats pushes up harvest, profits and investments in an even larger fishing fleet. At the same time, balancing feedback occurs as more harvesting means scarcer fish, which become more expensive to catch, reducing profits and lowering investments (Meadows and Wright 2008). Again, different feedback loops may dominate a system at different times.

In one situation, fish population and fleet size are in equilibrium, which can potentially maintain a steady harvest rate forever. However, a minor change can radically alter the outcome. Equivalent to the introduction of enhanced recovery technology in the oil industry, the introduction of bottom trawls or sonars maintains the yield per boat for just a bit longer despite dwindling fish populations. This can lead to overshoot and oscillations[2]. With technology becoming even more efficient, the industry can wipe itself out entirely (Meadows and Wright 2008). This has been the fate of industrialised fishing in many parts of the world and there is evidence that we are now reaching global limits as well (Clover 2008). Again, technology functions as a catalyst that precipitates existing processes of growth and depletion. The dynamics may change with the introduction of fishing quota or other management systems, but this does not change the specific role of technology within the system, which is the focus of this paper.

Acknowledging the methodological limitations, the Global Footprint Network (2012) estimates it now takes the Earth one year and six months to regenerate what renewable matter we use in a year. In other words, stocks can act as buffers; the outflow from a stock of renewables can be temporarily higher than the inflow into that stock, but it will have to be compensated by lowering the outflow at some point in the future. So while non-renewable resources like oil are stock-limited, renewable resources like fish are flow-limited[3]. Similarly, if the rate at which we generate wastes exceeds the environment's ability to absorb them, this will have to be reversed in the future. For example, oceans and terrestrial ecosystems absorbed roughly 315 of a total of 555 gigatonne of accumulated anthropogenic carbon emissions (GtC) in the period 1750-2011. According to the IPCC, we have 50% chance of avoiding dangerous climate change if emissions stay below 840 GtC (Stocker et al. 2013). While emissions continue to grow, the absorption capacity of carbon reservoirs is limited and will eventually tail off (Ballantyne et al. 2012). There are biophysical limits to the amount of waste that can be

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[2] Overfishing one year occurs at the expense of catches in the following year. Balancing feedback (fewer fishing boats) temporarily brings back fish populations, but overfishing reoccurs again the next season.

[3] Strictly speaking, fossil fuels are also flow-limited if we can wait long enough for them to form. The process for currently exploited coal/oil/gas reserves is believed to be on the order of millions of years.

stored by the environment (the finite size of a sink[4]) and to the magnitude of the waste flows that can be absorbed and cycled over time (the renewable capacity of a sink) (Daly and Townsend 1993).

The simplified dynamics of the oil and fishing economies help us understand basic biophysical limits to the flows between engineered and natural systems in a quantitative sense. These flows also have certain qualitative characteristics that need to be taken into account. For this, we draw from the field of thermodynamics: a branch of physical sciences concerned with how energy changes from one form to another.

2.2 Thermodynamics

Thermodynamics states that energy can neither be created, nor destroyed; it can only change form. With a melting ice cube, heat transfers in one direction: from the surroundings to the ice. The heat lost by the surroundings equals the heat gained by the ice cube. The process will continue until there is equilibrium and the water has evaporated. Heat transfer from a colder system to a warmer environment can only be done by applying “work”. A fridge performs this work by taking heat out of the water in the ice cube tray inside the compartment and transferring it to the warmer kitchen. Thermodynamics also states that no energy transfer is 100% effective because of losses. In our example, it means that more heat is pumped into the kitchen than the amount of heat removed from the ice tray because of heat losses in the fridge’s electric wiring and from friction in the compressor.

Here, a distinction should be made between exergy and energy. Exergy represents the work potential, i.e., the useful portion of the energy used by the fridge to freeze water in the ice tray. While energy cannot be destroyed, exergy can. In other words, the fridge degrades some of the useful electricity into useless disorganised heat dissipated in the room. Energy is always tending toward more disorganised forms. The overall result is an increase in the degree of disorder or randomness, which is called entropy. We can see this in nature; everything perishes, rots, decays, falls apart and has the tendency to go from order to disorder[5]. In our example, the fridge and its components will eventually break down if we fail to apply work for their maintenance. The whole industrial system producing the fridge is bound to the same rule. Refineries transform crude oil into hydrocarbons and plastics; factories transform the hydrocarbons into kinetic energy, thermal energy and carbon dioxide emissions. Plastics degrade and end up in the environment in the form of micro- and nano-particles. This sequence of transformation increases entropy (decreases order).

The increase of entropy on earth as a whole is reversed only because of the existence of a complex biosphere powered primarily by solar radiation, which represents the main source of work and inflow of exergy. After most of this exergy is reflected back into space, some of it is transformed by plants and organisms into chemical exergy and some of it eventually ends up buried as low entropy stocks of carbon, coal, oil and gas. Flows of energy on earth are part of an open cycle; solar exergy comes in and heat goes out. Flows of matter on the other hand are part of a closed cycle (Boulding 1966). Ecosystems are driven by high-exergy and low-entropy resources, and generate almost no waste. In contrast, engineered systems are driven

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[4] A sink is a place in the environment where a compound or material collects. It can provide a natural pollution removal process or act as a reservoir that takes up a pollutant.

[5] These changes are not only caused by entropic transformation, contributing factors include gravity, earth movement, wind, weather, solar radiation, oxidation and human use (Corning 2002).

by the extraction of low-exergy resources. At the other end, they produce, accumulate and dispose high-entropy emissions and waste (Nielsen 2007). This flow of energy and matter from ecological sources through the economy and back to ecological sinks has been referred to as “throughput” (Daly and Townsend 1993).

The distinction between natural and engineered systems does not mean that the former are purely frugal and cyclical, or that the latter are purely wasteful and linear. Many industries rely on the recycling of matter and energy from production processes and from consumption wastes. At the same time, the biosphere “dumps” carbon, coal, oil and gas in natural landfills (Jensen et al. 2011). While it is therefore wrong to set natural and engineered systems on opposite sides of a spectrum, there are nevertheless important differences. Nielsen and Müller (2009) argue that in natural systems, the cycles are local, decentralized and develop towards being increasingly closed with decreasing emissions and waste as a consequence. In engineered systems, however, the cycles are increasingly global, transport-intensive and have evolved to be open with increasing emissions and waste as a consequence. Waste control generally reduces profitability; costs therefore tend to be externalised.

3. An ecological reality check

For industrial systems, a low throughput of matter and energy implies a smaller ecological footprint and greater life expectancy and durability of goods and infrastructure; a high throughput implies more depletion of resources that will need to be renewed and more waste that will need to be disposed of (Meadows and Wright 2008). System dynamics and thermodynamics tell us that a tolerable rate of throughput and entropic transformation is ultimately dictated by the natural system, not by economics or engineering.

A possible task for engineering, within limits, would be to maximise the durability of stocks by minimising inflows of low entropy natural resources and by minimising outflows of high entropy waste and emissions. The role that industrial societies have assigned to technology is, however, much more Herculean. We have asked it to simultaneously and boundlessly minimise environmental impacts and maximise economic growth. In 1966, Kenneth Boulding suggested: “We are very far from having made the moral, political, and psychological adjustments which are implied in this transition from the illimitable plane to the closed sphere” (Boulding 1966: 2-3). How far are we now, almost half a century later?

3.1 Technology and substitution

Daly and Townsend (1993) see three dominant views in society. Some simply dismiss ultimate general scarcity on earth. Others accept the idea, but perceive the world as sufficiently large relative to the scale of human activity. Many have attempted to quantify the claim that engineered systems place on planetary resources (Vitousek et al. 1986; Haberl et al. 2007). There is tremendous uncertainty in the estimates, not in the least in determining the maximum scale that would lead to crisis levels (O’Neill 2011). A third dominant view in society sees human ingenuity and technical efficiency as the ultimate resources. There may be others, but the last position is the most interesting for the purposes of this paper.

While its rise to ascendency is relatively recent in human history, capitalism in different shapes continues to spread as the “operating system” for most economies in the world. It operates on the assumption that the output of production is a function of capital, labour and natural resources; shortages in the third factor elicit development of substitutes and higher efficiency in the first two factors. The suggestion in economic textbooks is generally that natural resources are not a limiting factor (Solow 1974; 1997). If we follow the logic of the production function we could ultimately bake a cake with only the cook and his kitchen; we do not need flour, eggs and sugar. We could also make our cake a thousand times bigger with no extra ingredients, if we stir faster and use bigger bowls and ovens (Georgescu-Roegen 1975; Daly 1997). In reality, of course, there are biophysical limits. The response to this is generally that markets will adjust production to impending environmental constraints (Solow 1997; Stiglitz 1997). While this may indeed occur at a local level, the real question is whether this will also occur at the aggregate scale of the global ecological envelope.

3.2 Decoupling, efficiency and effectiveness

Virtually all economies are currently growing both physically and financially, within a global envelope that is finite, non-growing and materially closed. A prevailing view, such as within the OECD and UNEP, is that the physical growth of throughput can be decoupled from the non-physical (financial) growth of GDP through innovation, which is commonly branded as “green growth” or “sustainable growth”. This view is also reflected, for example, in policy proposals for the next United Nations Climate Change Conference that emphasize decoupling emissions from growth (European Commission 2014). Two forms of decoupling are discussed in the literature: With relative decoupling, the growth of environmental impacts slows down relative to GDP due to efficiency improvements. With absolute decoupling, the environmental impact decreases as GDP grows (OECD 2002; Fischer-Kowalski and Swilling 2011).

To perpetuate a growing GDP under conditions of absolute biophysical limits will require—it is argued—compensation in terms of absolute decoupling of both the inflows from and the outflows into the environment[6]. Relative decoupling will not suffice; it will merely delay the point in time when one or more limits are reached (Blauwhof 2012). Moreover, absolute decoupling will have to be achieved on a global scale, because improvements in one part of the world might be achieved when production and associated ecological impacts are moved offshore (Bunker 1996; Bringezu et al. 2004).

There is evidence that global absolute decoupling has not occurred for important inflows of energy and matter. Global electricity consumption grew by 3% per year in the period 1980-2001. Reflecting improvements in energy efficiency as well as a shift towards less energy-intensive industries, global energy consumption still grew at a rate of 1.7% (EIA 2014). In the period 1980-2008, the amount of energy and raw materials required to produce a dollar of world GDP was reduced by 20%. At the same time, world GDP (in constant prices) grew by 125% such that total resource use still increased by 79% (SERI 2013). Only relative decoupling has been achieved (see Figure 1).

Turning now to the question of decoupling the outflows of waste and emissions, some have used carbon dioxide (CO_2) emissions as a proxy for other outflows. Global Real GDP (adjusted for inflation) grew by 3% per year in the period 1980-2001 and global CO_2 emissions grew 1.2% per year in the same period (EIA 2014). Between 1996 and 2006, these figures were 3.1% and 2.4%, respectively (Mitchell 2012). According to the IPCC, economic

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[6] Strictly speaking, we should speak of “negative coupling” because GDP growth and throughput are still coupled; the coupling is simply functionally different (Smith and Max-Neef 2011).

growth was the main driver for global greenhouse gas emissions to grow more quickly between 2000 and 2010 than in each of the three previous decades (Edenhofer et al. 2014). Only relative decoupling has been achieved (see Figure 1). It is important to note that a trend in a subset of pollutants, such as CO_2, says little about the total environmental degeneration caused by a society. Some have suggested that energy use is a better approximation and this has never decreased in absolute terms anywhere with recorded GDP growth (Smith and Max-Neef 2011).

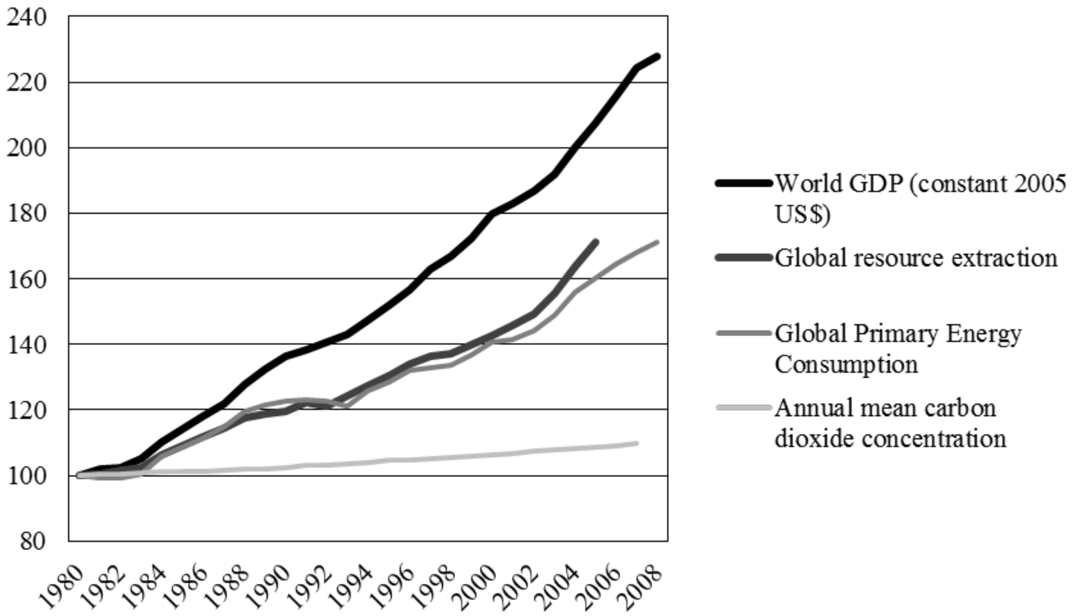

Figure 1 - Relative decoupling of growth from matter and energy flows.

Sources: World GDP, Resource extraction, Energy consumption, CO_2 concentrations based on World Bank (2014), SERI (2013), EIA (2014) and IPCC (2014), respectively.

We might be tempted to think that relative decoupling is only the first step towards absolute decoupling. However, relative decoupling is by no means a new phenomenon. Bunker (1996) describes how raw-materials-saving processes are older than the industrial revolution. Since the 16th century, innovation increased the strength per unit weight of metal, reduced the amount of copper required to transmit electricity, brought down the weight of charcoal needed to produce a ton of iron and so on. More efficient production processes replaced their more material-intensive predecessors, but they did not slow down the absolute growth of inflows of matter and energy (Bunker 1996). If relative decoupling indeed precedes absolute decoupling, the transition is seriously protracted.

There is also reason to believe that relative decoupling in the current economic system is making matters worse. Not only did the age-old dematerialisation strategies fail to neutralise overall growth of material production and consumption, they actually fuelled it. In economics, this process, known as the Jevons' paradox, was first described in 1865. The strategies contributed to reducing unit costs of production, which accelerated the circulation of capital, which in turn cheapened and intensified the appropriation of more natural resources. This represents reinforcing feedback whereby technology acts as a catalyst for increasing throughput. Dematerialisation has therefore usually been temporary, reflecting the lag between the cost reduction and the expansion of production (Bunker 1996; Bringezu et al. 2004).

The question that comes up is whether the process of relative decoupling through efficiency improvements can make way for a process of absolute decoupling and ecological recovery through an entirely different set of engineering strategies. A distinction is therefore sometimes made between eco-efficiency and eco-effectiveness. The former improves by reducing the added environmental impact while maintaining or increasing the value of the output produced. The latter focuses on the development of products and industrial systems that maintain or enhance the quality and productivity of materials through subsequent life cycles (Braungart et al. 2007).

We will now explore how leading environmental engineering concepts and frameworks address either efficiency or effectiveness.

4. Environmental engineering and false expectations

From the above, it is clear that flows of matter and energy through the global economy have increased in absolute terms. Technological eco-efficiency has not been able to compensate for the expansion and may even have added fuel to the fire. Nevertheless, the mainstream sustainable development movement has trusted heavily in technology for solving the conflict between growth and the environment (WCED 1987; Weizsäcker et al. 1997; Schmidt-Bleek and Weaver 1998). This position is again very prominent in the eco-economic decoupling and green economy discourses (Brand 2012).

Several approaches with strong engineering content help perpetuate the promise:

1. The cradle-to-cradle framework “posits a new way of designing human systems to eliminate conflicts between economic growth and environmental health resulting from poor design and market structure” (McDonough et al. 2003: 436).
2. “Industrial Ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution” (Graedel and Allenby 1995: 9).
3. Natural capitalism incorporates “business strategies built around the radically more productive use of natural resources [that] can solve many environmental problems at a profit” (Lovins et al. 1999: 145).
4. The circular economy aims for a “transformation of products and their associated material flows such that they form a supportive relationship with ecological systems and future economic growth” (Ellen MacArthur Foundation 2013: 23).

There is overlap between the approaches, but their principles can be categorised as operating at different economic scales. Some are concerned with environmental pressures of the output of production, i.e., consumer products and services; others with environmental pressures at the production system level. The following paragraphs probe the expectation that these approaches will enable continued economic growth in an environmentally benign way in the long run. The conclusion is that such a view ignores, misinterprets or underestimates the biophysical limits outlined by the system dynamics and thermodynamics perspectives.

4.1 Overestimating approaches at the product level

Only "1% of all materials mobilised to serve America is actually made into products and still in use six months after sale" (Lovins et al. 1999: 152). Not only is there scope to redesign products in ways that reduce the squandering of material resources during manufacturing, there is also scope to reprocess much of the waste matter and (components of) the discarded products themselves.

Ecodesign, or "cradle-to-grave" design, seeks such improvements by considering the whole lifespan of a product[7] (Brezet et al. 1997), but it has been criticised for placing the onus on consumers to dispose of products responsibly and for failing to address the physical limitations of the recycling process itself. While some materials like pure steel, aluminium, copper can be recycled indefinitely; others, such as paper, wood and plastics, can only make it through the process a limited number of times before they are disposed in landfill or incinerated. This can also happen with metal because of hard-to-separate impurities or because they are generally mixed into alloys. A typical soda can, for example, consists of two kinds of aluminium which are melted together during recycling, resulting in a weaker product (McDonough and Braungart 2002). At each cycle some of the matter is lost or degraded; recycling is really "down-cycling" (Kay 1994: 14), reflecting the process of increasing entropy. Cradle-to-cradle design therefore proposes closed-loop approaches where "waste equals food" (McDonough and Braungart 2002). It takes the view that zero-waste will never be realised because this would contradict the laws of thermodynamics. "The quantity of the emissions is not the problem, it is the quality of the outputs that must be addressed by making the emissions healthy" (Braungart et al. 2007: 6). The literature suggests that this type of eco-effectiveness can be achieved when products and their components are designed to consist of technical and biological "nutrients". The former will permanently move as pure and valuable materials within closed-loop industrial cycles. The latter will easily re-enter the water or soil without releasing synthetic materials and toxins.

This proposed strategy is not without risk and uncertainty. First, the permanent movement of "technical nutrients" in closed cycles would violate the entropy law for most industrial materials as mentioned earlier (Reay et al. 2011). It is unclear whether those materials can all be phased out and replaced with appropriate materials, at a profit. Second, the manufacturing of "biological nutrients" depends on large quantities of plant materials. This will increase the scale of human appropriation of the stocks and flows of the natural system through agro-industrial production. This will likely aggravate the age-old impacts of agriculture on biodiversity, soil quality and water availability. It will also add a third rival in an already tense "food versus fuel" competition over agricultural resources. Meanwhile, increased waste and emissions consisting of biological nutrients would participate in biogeochemical cycles. An increase of inputs in those cycles can cause significant environmental damage, such as eutrophication from nutrient enrichment for example (Reijnders 2008).

One only needs to look around at what is on sale in shopping malls to see that cradle-to-cradle is much less widespread than another form of product engineering: design for obsolescence, which is defined as a deliberate strategy of making a product become rapidly out-dated or unserviceable in order to ensure continual sales. It represents a positive development from a narrow yet dominant commercial perspective. Philip Kotler, for example,

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[7] The lifespan of goods consists of raw materials acquisition, manufacturing, transportation, distribution and use to final recycling and disposal.

stated that this is “the working of the competitive and technological forces in a free society—forces that lead to ever-improving goods and services” (The Economist 2009). Were cradle-to-cradle to be taken up, it is likely that these commercial forces will generate products consisting of recyclable or biological materials with very short life spans. As suggested by a leading European carpet manufacturer: “cradle-to-cradle makes planned obsolescence good” (Sibley 2011). Such a view ignores earlier mentioned agricultural and biological concerns.

Others have proposed to respond to the problem of obsolescence by replacing disposable consumer goods with so-called product-services (Stahel and Reday 1976; Hawken et al. 1999; McDonough and Braungart 2002). “Services” in the sense used here focus on the utilisation and performance of goods, as opposed to the conventional definition of financial, health and education services. For example, Xerox sells reproduction services instead of photocopiers and Interface sells floor-covering services instead of carpets. The rationale is that it is in the interest of the manufacturer to avoid “leasing” products that quickly become defective. The idea has been around for a long time, but it hasn’t fundamentally altered patterns of consumption. In the current economic and cultural setting, such a system does not (yet) significantly compete with rental systems or private ownership (Reay et al. 2011). Whether it will is not a key issue in this paper. A more relevant concern is that product-services also rely on a biophysical basis for their production, use and replacement (Tukker et al. 2006). In a growth economy, product-services will also lead to growing throughput, which will also eventually hit some form of limit.

An inherent constraint of environmental product design strategies is that even if the individual impacts of a product were minimised, the increasing flow of total products sold and disposed would lead to a rise of the aggregate ecological cost. A few examples have already been discussed. Another limitation is that the strategies do not address the structural environmental challenges of current modes of production. Some have therefore sought to redesign entire industrial systems.

4.2 Overestimating approaches at the industrial level

In *Natural Capitalism*, Hawken et al. (1999) suggested that it is difficult to imagine the enormous potential for resource productivity, just as it was impossible 250 years ago to imagine the boost in labour productivity that lay ahead. Heat waste and discarded by-products are seen as evidence of profound inefficiencies. The authors claim that the U.S. economy is not even 10% as energy efficient as the laws of physics allow (Lovins et al. 1999). While they define efficiency in the engineering sense of doing more with less, measuring both factors in physical terms, they also suggest that this will save money. A relative decline in the volume of raw materials used per unit of GDP is assumed to lead to a process of absolute reduction in resource extraction and pollution (Hawken et al. 1999; Lovins et al. 1999). Advocates of the circular economy also expect that “the decoupling of growth from the demand for resources will slow current rates of natural capital erosion” (Ellen MacArthur Foundation 2013: 85). Both frameworks assume that relative decoupling leads to absolute decoupling.

The first objection to this assumption was discussed earlier. Historical evidence has shown that when you get more from less, you just take advantage of the slack (Bunker 1996). A second objection is related to the existence of a maximum efficiency limit. Perpetual financial growth within the confines of absolute biophysical limits is hypothetically only possible if efficiencies in the throughput keep perpetually rising faster than the rate of growth. As we know, the second law of thermodynamics dictates that efficiency can never improve above 100% (Blauwhof 2012).

Beyond eco-efficiency strategies that merely lead to relative decoupling, the natural capitalism and circular economy frameworks suggest developing industrial-scale eco-effectiveness strategies that will lead to absolute decoupling. Lovins et al. (1999: 10) suggest that it is possible to eliminate waste "by redesigning industrial systems on biological lines." Similarly, "the circular economy takes its insights from living systems" (Ellen MacArthur Foundation 2013: 26). They allude to the somewhat older concept of industrial ecology in which wastes from one industrial process can serve as the raw materials for another, thereby reducing environmental impacts (Frosch and Gallopoulos 1989) or even closing cycles of matter as occurring in natural ecosystems (Graedel and Allenby 1995). Half a century ago, Boulding (1966: 5) already argued that in a closed system "all outputs from consumption would constantly be recycled to become inputs for production, as for instance, nitrogen in the nitrogen cycle of the natural ecosystem".

To be clear, despite the oldness of these ideas, industrial ecology does not yet exist in a strict sense. Most of the current examples consist of technical or operational modifications for reducing waste in individual firms. The inter-industry coordination that does exist today relies on cascading waste into feedstock. This is a practice that can reduce (or slow down the growth of) material throughput, but it does not close material cycles (O'Rourke et al. 1996). Following China's vision of a circular economy, for example, there have been worthy efficiency improvements in the establishment of matter and energy exchanges within eco-industrial parks. However, resource consumption and waste generation continue to increase (Tian et al. 2014). It is difficult to imagine closing a system that imports such vast amounts of raw material inputs and exports over a third of its production output (as fraction of GDP in 2006) (Koopman et al. 2008). For now, the Chinese economy seems more "spiralling" than "circular".

If it did occur in the future, a widespread adoption of industrial ecology principles would have to deal with the matter of entropy. As we increase recycling at the industrial scale, we diffuse and loose more and more matter at each cycle and we generate growing waste and emissions (Daly and Townsend 1993). Approaching closed material cycles would then require separating and reprocessing high entropy wastes to return and reuse them as low entropy resources (O'Rourke et al. 1996).

It is quite possible to re-concentrate diffused materials, but such a reduction of entropy has to be paid for by inputs of energy. An industrial-scale shift from virgin to reprocessed materials will produce shifts in energy use. On the one hand, producing a ton of steel plate from iron ore is almost four times more energy intensive than recycling steel (Daly and Townsend 1993). On the other hand, recycling chemicals, such as solvents from dilute industrial waste streams, may result in net energy costs (O'Rourke et al. 1996). Whichever way the balance would initially tilt, in the end, full-scale industrial ecology within a growth-based economy will demand growing energy inputs. Hopes are set on solar-powered electricity generation and its non-damaging bountiful source of exergy. However, such a system also requires a material basis for the construction of solar cells, the transportation and storage of electricity. Its growth will also lead to increasing waste heat. "In regard to the energy system there is, unfortunately, no escape from the grim Second Law of Thermodynamics" (Boulding 1966: 6).

Even with infinite sources of renewable energy, closed cycles remain difficult to imagine for complex materials such as pesticides, fertilisers, coatings, lubricants, adhesives, inks, brake pads or tyres. It is even harder to imagine for highly dissipative emissions resulting from the combustion of fossil fuels (O'Rourke et al. 1996). Industrial ecologists, natural capitalists and circular economists therefore argue that these materials can be phased out, also without threatening economic growth. The case that is brought up time and time again, perhaps for lack of alternative, is that of the cutback in chlorofluorocarbons, which simultaneously delivered windfall profits for business. However, this took place in very specific economic and political circumstances. For many reasons, this hasn't reoccurred on such a scale for other toxic and dissipative materials (Maxwell and Briscoe 1997).

5. Conclusions

This paper started by asking what role can realistically be assigned to engineering, and when we would need to look beyond technology towards economic and social changes.

Environmental engineering has so far failed to bring about the level of absolute decoupling that is required to sustain the current economic system. Present expectations of dematerialisation, recycling and loop-closing should be tempered by the fact that these engineering principles have been around for a very long time and that their environmental gains have been overwhelmed by economic growth. Several practices and concepts with strong engineering content nevertheless promise an absolute reduction in the environmental impacts of production and consumption systems in growth-based economies. For several reasons, this is a false promise.

Cradle-to-cradle overestimates the potential to close (growing) cycles of "technical nutrients". It also ignores or underestimates the impacts of a shift to "biological nutrients". Industrial ecology, natural capitalism and the circular economy framework overestimate the capacity to close (growing) matter cycles in production systems (particularly when dealing with toxic or dissipative matter). Their proposed shift from products to services ignores or underestimates the required physical basis. Their advocates also ignore or underestimate the fact that energy cannot be cycled and the consequences for energy inflows and heat waste outflows. In general, thermodynamic considerations are not receiving sufficient attention in the cradle-to-cradle and industrial ecology literature. These doubts are also pertinent to the natural capitalism and circular economy literature that relies heavily on cradle-to-cradle and industrial ecology principles.

Within a growth economy, the adoption of these engineering practices and concepts might slow down the growth of throughput. At best, this merely delays the time it takes to reach the boundaries of the biophysical envelope. At worst, the resource and energy savings generate profits that are reinvested in growth, which doesn't delay, but speeds up depletion and pollution. The field of system dynamics may help to mentally reconcile these seemingly conflicting dynamics. Different feedback loops might dominate and drive (parts of) the system in different directions at different times.

An appreciation of biophysical limits and thermodynamics should be much more prominent in the fields of economics and engineering. The insights tell us that there are limits imposed on the quantity of non-renewable resources, the pace of regeneration of renewables, how much emissions nature can neutralise, how quickly wastes can be absorbed, how often materials can be recycled, and so on. Although not in the scope of this paper, this brings up important questions about social and economic equity. As we cannot increase the size of the pie indefinitely, there are ethical and political concerns about its persistent and worsening lopsided distribution (Rammelt and Boes 2013).

In conclusion, our economies must vastly be remodelled despite the engineering illusions that vindicate business as usual. “Clean coal” is an obviously deceitful example of this, but even our more genuine technical efforts cannot fully close material cycles and certainly cannot close energy cycles. Perhaps they do not need to. The natural system has the capacity to absorb a certain amount of our waste and pollutants. It also has the potential to generate a constant inflow of renewable resources. Within bounds, engineering could serve to maximise the durability of stocks by minimising throughput. The engineering concepts and frameworks discussed in this paper surely have something to offer in this regard, but they will end up chasing their tails if we do not address the social and economic forces driving up production and consumption. This expansion is instigated by the economy and catalysed by technology, but is eventually bound by ecology.

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