Gap Analyses of Environmental Management Frameworks for Nanotechnology

Michael R. Greenberg*

Abstract— Nanotechnology is a rapidly growing field fraught with uncertainty due to the still nascent efforts to understand its potential health risks and ecosystem dynamics. Yet, nanotechnology, like other still-emerging technologies, provides fertile territory for establishing an “upstream” management system that minimizes future risks while still in research and design. Thus, to identify the characteristics of such a proactive nano management system, gap analyses were performed on the sustainable engineering frameworks: Twelve Principles of Green Engineering, Earth Systems Engineering and Management, Life Cycle Assessment, and Cradle to Cradle, with economic, socio-cultural, environmental, and technical criteria, using buckyballs (endohedral metallofullerenes), as a case study nanomaterial. It was determined that, partly due to the unavailability of most quantitative life cycle data, and the need for modifications of these frameworks to function both as proactive as well as nano-specific, it is premature to identify a specific optimal framework. Thus, a “hybrid” framework made partly from the tools, principles, and values of the existing methods like the ones analyzed here is proposed.

I. INTRODUCTION

Great recent progress has occurred in sustainability: maintaining or improving environmental, economic, and social conditions indefinitely. Reactive, pollution-treating approaches are yielding to proactive, visionary sets of interdisciplinary principles and practices defined here as “environmental management frameworks” (EMFs). Deeper technological and socioeconomic issues can now be approached with management, design, and policy employing highly systemic thinking. Nanotechnology (nano) provides an unprecedented though big opportunity for sustainability. Yet, difficulties arise since nano challenges the rules of policy, regulatory, workplace practices, and sustainable (green) design. Nano is a paradigm shift in familiar bio-physical realities, with uncertain real-world interactions, and possible drastic changes in organization and management of production, communications infrastructure, and increased productivity that could change the face of industrialization sufficiently to outmode previous regulatory assumptions.

Nanoparticles are ultrafines smaller than 100 nm (i.e. microorganisms, dust) but nanomaterials are designed for use in advanced industries with novel properties such as greater material strength, enhanced reactivity, better catalytic functioning, and higher conductivity. Nano is booming, with 800+ firms worldwide and available products such as nanotitania sunscreens, stain-resistant fabrics, and ultra-light displays. US public research is $1 billion annually and global output may exceed $1 trillion by 2015. While both proponents and opponents of nano feel strongly, there simply exists too little environmental data to support either side. Environmental implications of nano remain elusive, with sparse toxicology, typically on older nanomaterials such as carbon nanotubes. Given accelerating technological change, the environmental community’s response ability is further lagging. Needed then is foresight in governance and incentives and methodologies for industry to “green” itself while regulations catch up. Despite these daunting challenges, nano presents an attractive area for pilot testing some EMFs. Because nano is an emerging industry, it allows “upstream” management to minimize risk while still in R&D, before its infrastructure is cemented. It is a chance to facilitate the co-development of ethical and environmental design to accompany R&D that is “intentionalized” or accounts for higher-level perturbations in the systemic human/environmental model still outside the scope of typically measurable technological and human and environmental health effects. Nano is environmentalism’s first opportunity to shape an emerging technology in ways that could dramatically improve environmental conditions. However, since many of these EMFs have their roots in conventional environmental thought, i.e. reactive, not proactive, additional obstacles are created. Adding to the complexity, parallel work is being conducted in a subset of green chemistry known as “green nanoscience”. Nanomaterials and “nanomanufacturing” methods can themselves develop as pollution prevention technologies.

The unavailability of environmental, toxicology, and life cycle energy/material data makes evaluation problematic. Thus, this paper proposes an initial, qualitative framework of EMF(s) developed to manage nano. Thus, more specific issues such as how to integrate, sort, and rank particular data must be delayed. Also, the quantity, type, and nature of the data that become available may necessitate modification. Yet, present uncertainty allows greater degrees of freedom for interdisciplinary, multi-stakeholder delineation of goals, risks, incentives, etc. that need inclusion in any EMF.

The EMFs evaluated for management of the case study nanomaterial, endohedral metallofullerenes (trademarked Carbon Trimetaspheres) are: 1) Earth Systems Engineering and Management (ESEM), 2) Twelve Principles of Green Engineering (12P), 3) Life Cycle Assessment (LCA), and 4) Waste equals Food (Cradle to Cradle or C2C). Though these

---

*Manuscript received March, 2006.

Author (mrg5x@virginia.edu) is a MS candidate at U. Virginia, Systems & Information Engineering Dept, PO Box 400646, 151 Engineer’s Way, Charlottesville VA 22804; U.VA professors Michael Gorman (meg3c@virginia.edu) & Garrick Louis (gel66@virginia.edu) advised.
EMFs are widely divergent in scope, they provide a wide base of problem definition tools, data usages, philosophies, and targeted stakeholders. Thus, it is desired to see which of the EMFs are most useful now, and more importantly, show more potential for development of some “hybrid” EMF that is nano specific or inclusive. It is assumed that the choice of the four EMFs is ultimately insignificant since many future iterations will occur as data becomes available. Also, these EMFs are not discrete but are an overlapping continuum of approaches. In fact, some may even “nest” within others due to their vast differences in scale. There may even be some fundamental incompatibilities between these EMFs. However, the insignificance assumption delays these issues.

This study uses “gap analyses” to assess the implications and overall applicability of the selected EMFs to Trimetaspheres, and to nano in general. Criteria include: 1) economic, i.e. will they add net cost or net value? Will they help create incentives and market opportunities; 2) technical: ease of implementation, adaptability and flexibility, narrowness vs. vagueness, and predicted ability to process, correlate, communicate, and prioritize quantitative data and other information; 3) environmental: greatest overall benefit to planetary and human (worker and citizen) health, creating a climate of advancing the tenets of sustainability; 4) and socio-cultural: adequate consideration of stakeholders and their values, cultural acceptability and portability.

The measurement of these criteria is itself an evolving element and is largely subjective. The criteria themselves may later be modified because, at least for environmental criteria, a “single score” metric is still controversial. Also, due to the arbitrariness of chosen criteria, it will be desirable to perform a sensitivity analysis to determine how these assumptions propagate through the analysis in future iterations. Thus, the comments and conclusions drawn during this evaluation are better thought of as hypotheses for future evaluation. Since it is predicted that none of the EMFs selected here will be adequate without extensive rethinking and retooling, it is also desired to look for synergies in existing approaches and also point out possibilities for fresh approaches and future research.

Carbon Trimetaspheres typically consist of a 80-C sphere with three Lanthanide series metal atoms bounded by an N inside the sphere. Carbon spheres are molecules termed as fullerenes (popularly, buckyballs). The are created under extreme and chaotic conditions such as running an electric arc through a graphite rod with some reactants and catalysts at temperatures exceeding 3000K or near stars, and are very stable in extreme temperature and chemical conditions. While “empty-cage” fullerenes were one of the first discovered nanoparticles (in 1985, and named after R. Buckminster Fuller’s geodesic domes), their myriad hoped applications have fallen short. Metallofullerenes, however, promise better results in similar applications (i.e. lubricants, self-assembled monolayering, nanocomputing devices, superconducting wires, antifriction coatings, photovoltaics, diamond films, drugs and drug-delivery systems).

Trimetaspheres, discovered in the mid-1990’s at the Virginia Polytechnic Institute by Harry Dorn and colleagues, is licensed to Danville, VA based Luna Innovations, who along with Dorn still research chemistry, manufacturing, environmental fate and transport and toxicology issues. Currently, this nanomaterial is still made by tightly packing metals and catalysts into hollowed-out graphite rods placed at opposite electrodes in an arc generating chamber. The arc vaporizes the carbon and other compounds in the electrodes and leaves a sooty deposit containing the gamut of carbon nanomaterials, including empty-cage buckyballs and heavier Trimetaspheres. Desired products are purified and separated, typically with solvents such as toluene, and with tools such as gel chromatography. Much of the data on other parameters such as current, pressure (or vacuum), and what type of atmospheres that optimize yield, purity, and composition remain largely protected trade secrets.

One potential lucrative application is Magnetic Resonance Imaging (MRI) image enhancement. Trimetaspheres containing the gadolinium, a toxic rare-earth element, could be altered to be water soluble and injected into a patient prior to scanning (similar to other existing imaging agents – an estimated $1 billion annual market), but yielding better definition of small details. Also, the spheres might be alterable to seek specific organs and cell types. Further, the high stability of the fullerenes by virtue of the cage surrounding the metal, theoretically protects the person from harm, though the ultimate fate and toxicity is unknown.

II. EVALUATION OF EMFS

A. Earth Systems Engineering and Management

ESEM is a framework being developed by Brad Allenby, former Environment, Health and Safety Vice President for AT&T and current civil engineering faculty member at Arizona State University. ESEM is “the capability to rationally and ethically engineer and manage human technology systems and related elements of natural systems in such a way to provide the requisite functionality while facilitating the active management of strongly coupled natural systems”. It is a uniquely systemic approach to sustainability where “engineering” and “management” does not limit it more to these fields than the others which help to build, understand, and manage this big picture. ESEM is not unique, only stronger, in asserting that the environment and humanity can no longer feasibly be viewed as distinct, but rather that our technological, cultural, and economic systems now so greatly dominate our planet that we must view it as the “human Earth”. Allenby predicts that the three dominant, and convergent, technologies in the future will be nanotechnological, biological, and information systems.

“Increasingly integrated, complex, and global behaviors” make traditional engineering approaches or the bio- physical sciences alone inadequate. ESEM, unlike other approaches, is not solely geared towards producing specific “artifacts”,
but rather “dialogue with the complex natural and human components of earth systems”. ESEM’s objectives and constraints aim to preserve and rebuild desired ecological communities while maintaining human activity at a politically acceptable level. However, because the complex systems themselves cannot be completely controlled, “adaptive management” contingencies for complex “cognitive-technical-natural” systems are added: solutions must balance flexibility and redundancy (factors of safety) and decisions should be “reversible” in case of emergency.

ESEM demands that we start assuming moral responsibility for understanding how our design, management, and policy decisions affect earth systems at all scales. Thus, collaboration and data sharing on an inter-industry and interstate, and indeed, international level is needed. New institutions to support widespread adoption of ESEM would be centralized and transparent: a vast nonpolitical consortium or a network hub for sustainability data, standards, information, guidance, and collaboration.

First, to evaluate the economic considerations of using ESEM to manage Trimetaspheres, we will examine whether it will add net cost or value and whether it would create incentives and market opportunities. The issue of adding value here is tremendously ambiguous. If one were to make the logical assumption that a functioning, sustainable Earth at some point would have widespread adherence to many of the principles put forth in ESEM, then it would be fair to say that a firm’s decision to adopt ESEM would align it with the economic and market realities in the long run. In the short run, the unfamiliarity and ambiguity about the novel technical and non-technical elements could require costly outside consulting, potentially causing shareholder resistance. Also, unclear is how the language of ESEM aligns with the immediate scientific, technological, and R&D needs of nanomaterials, thus we might have to wait until the more practical and specific aspects of ESEM are developed before it can be tailored for this specific application.

On technical criteria, concerns are similar to the economic ones. Ease of implementation is ambiguous as ecosystem management is quite difficult to predict given the dearth of such data available for Trimetaspheres. However, when such data arrives, ESEM may be a readily adaptable approach because of its built-in flexibility language. And, insofar as ESEM relies on well-understood and practiced EMFs such as LCA, the ability to process, correlate, communicate, and prioritize quantitative data and other information should be comprehensive. However, full implementation requires that we develop the language and comprehension of the “expression of intentionality at the level of highly complex and broadly scaled cognitive systems”, indicating large present technical gaps. If a firm is to act rationally and responsibly, they must consider not only conventional data, but further “the nature of the complex systems within which one is embedded,” as tremendous technical challenge indeed, especially since nano is fraught with unknowns.

Allenby recognizes that ESEM is in an infant stage and that most of the supporting knowledge and infrastructure needed does not yet exist. Thus, it is proposed as an EMF to build on existing industrial ecology methodologies such as LCA. In this sense, insofar as it is adoptable, it would advance the tenets of sustainability by taking advantage of the existing older, more basic, and more well-known EMFs while providing a comprehensive context of the systems in which an industry is embedded in that can be used when expanding and refining environmental programs later. ESEM is ambitious; asking us to “begin at the beginning, with an exploration of how we think, and how we know” both individually and at “complex cognitive systems” levels. Indeed, we indeed are at the beginning of our knowledge of what ecosystem effects we can predict from Trimetaspheres; knowledge needed before nanomaterials are widespread.

For social criteria, understanding the big picture context of decisions is paramount, and thus, with effective outreach, ESEM could possibly bring rationality and common ground to both the proponents and opponents of nano. This could help improve firms’ market image (economic benefits) and liability issues (environmental, economic benefits). Also, ESEM recognizes itself as needing to work within, rather than alter, political realities, improving cultural acceptance.

B. Twelve Principles of Green Engineering (12P)

12P is a set of synergistic principles for the design, discovery, and implementation of engineering solutions. It is based on a definition of sustainability as one that advances environmental, economic and societal goals. It is a scalable approach across the molecular, product, process as well as system levels. It promotes careful focus on entire life cycles to avoid shifting problems from one point (i.e. energy used in manufacture) to another (i.e. greater end-of-life burden).

12P’s book chapter lists its principles in detail, yet a few are highlighted as especially relevant for nano. First, it is clear that synthesis of Trimetaspheres is both material and energy intensive. Therefore, the first principle, that material and energy inputs and outputs should be as inherently non-hazardous as possible, strongly applies. As does the fourth, that mass, temporal and energy efficiency should be maximized. Lastly, environmental issues at the end of life cycles, i.e. issues regarding toxicity, persistence, fate and transport, and bioaccumulation make principle 10’s “after-life” performance metrics desirable.

Given economic criteria, while monetary costs or gains is largely conjecture due nano’s infancy, in the long run at least, reduced liabilities and operating costs could pay for initial and ongoing management efforts many times over. In the short-run, however, a mixed bag of both cost increases and decreases may occur. Reasons for added cost may include current lack of markets or income other than largely fixed grants and venture capital as well as the high R&D costs and barriers existing. But, savings may come from reduced resource usage, toxicity, and accidents, and higher efficiency. Regarding incentives, the high cost of
manufacturing due to material and energy intensity, and uncertainty of environmental and human health effects and associated potential future liability create strong motivation.

Next, for technical criteria, it is clear that 12P is intended for scientific and technological development for use by the engineer. Thus, in the case of Trimetaspheres, the combined efforts of various branches of engineering would have a practical guide developed with them in mind. In this sense, the ease of implementability and adaptability are both high. The principles use the language of efficiency, life cycles, performance metrics, and tradeoffs between competing objectives and criteria. Regarding narrowness/vagueness, the inherent scalability and conciseness of each principle ensures that the right ones are chosen in each application. As for the handling of data and information, 12P’s technical language provides a basis for how, when, and where data will be needed, processed, and correlated. Yet, the principles are only general guidelines and concepts, there is no large accompanying library of tools, black box or otherwise, to aid in the daunting challenge of actually employing them.

Regarding socio-cultural aspects of 12P implementation, there is a high degree of cultural portability since the language of engineering is similar to the language of science: concerned primarily with measurable quantities and with the facts, and is thus ostensibly free of ideological friction points. This values-neutral approach to sustainability should not encounter resistance other than from status quo in general, which itself is mitigated by nano’s infancy. However, since the principles are largely devoid of management, policy, and regulatory elements, it may be difficult for a firm to use them with all its connected stakeholders insofar as required. Also, the relative value-neutrality could have opportunity costs versus other approaches in terms of how the environmental community may respond and what kinds of larger, less measurable social benefits are achieved. While it could be argued that these aspects muddy the picture and reduce universality, it is conceivable 12P could result in a culture of “we’ve already done enough”-ism, i.e. an implicit assumption that social benefits are less important than technical ones. Non-economic benefits are “less” important in any for-profit organization by definition, but this does not alter the need for genuine sustainability. An understanding of the big picture of social, environmental and economic systems of which any nano firm is a growing subset, must be somehow considered whether it is a part of the chosen EMF or not.

Regarding environmental criteria, it does seem that 12P could advance of sustainability in nano. Its relative ease in technically employment makes short-run improvements likelier, and because of long-run economic need, 12P encourages sustainable design results. Yet it is unclear whether it is sufficient by the arguably broader and more stringent definitions of sustainability in the other EMFs discussed, save for LCA, which focus less on design choices made by particular organizations and deal more with visions for a rethought industrial landscape which, though more contentious, are perhaps ultimately more necessary.

C. Life Cycle Assessment (LCA)

The LCA discussion deviates from the evaluation criteria since it is assumed, as shall be seen, that LCA would be better adopted as a toolset within another EMF than used solo. Still, the issues raised by the LCA approach are important enough to merit separate discussion, and also demonstrates the need for newer comprehensive EMFs.

The Society for Environmental Toxicology and Chemistry defined LCA in 1882 as “a process to evaluate the environmental burdens associated with a product, process, or activity by identifying or quantifying energy and materials used and wastes released the environment; to assess the impact of those uses, and evaluate opportunities to affect environmental improvements”. The entire life cycle from material extraction, manufacturing, transportation, uses, and end-of-life, and also ecological health, human health, and resource depletion should all be considered. LCA is intended as a simplified physical system model.

However, for some time professionals have realized that LCA was not affecting product design as hoped. LCA is rooted in inventorying and thus the improvement step was being left out. Additionally, its use by consultants has yielded suboptimal results and lack of decision options to clients. In response, groups such as the Environmental Protection Encouragement Agency, founded by the C2C developers in Europe, developed re-tooled EMFs such as Life Cycle Development (LCD), which uses an explicit systems engineering approach that identifies components needing improvement, then iterates, changing the bounds of the investigation at each step though dynamic feedback to the improvement assessment activities. Yet, “original” LCA still has wide support and adoption such as Carnegie Mellon’s Economic Input-Output LCA web tools and also the Tellus Institute which have extensive built-in databases.

Informally, LCA is gathering all available information on material and energy flows in something’s life cycle. Thus, in this context, LCA is not a stand-alone EMF, but rather a set of tools for use in some larger management scheme. Thus, in this sense, LCA could allow for easy adoption economically and technically, at least for prioritizing the most crucial short-term issues regarding endohedral metallofullerenes. Because of the large support network and its familiarity, the actual steps involved in LCA versus the other EMFs here are more straightforward and hence less costly. Yet since LCA entirely depends on energy and materials data still largely unknown or unavailable to researchers, this creates a catch-22 in laying any management groundwork, demonstrating why starting with another EMF is preferable.

Still, LCA is popular and may provide a partnering basis with fullerenes manufacturers to share quantitative data and determine the extent of data needed for industrial processes. For Trimetaspheres, some examples might be the quantities of raw material inputs used such as graphite, lanthanide
series metals, catalysts, and solvents used in preparation and purification. Some issues LCA raises are: resources used in making and maintaining specialized equipment; balancing better yields with environmentally friendly production; manufacturing decisions affecting separation ease (thus greater control of material flows while avoiding unnecessary worker exposure; possible or cost effective infrastructure for both recycling used or waste materials (such other nanomaterials byproducts for use by other firms; and how different types of Trimetasphere or application affect efforts.

There have already been some initial efforts to assess the potential of LCA to manage nano indicating that LCAs are having difficulty assessing nano-specific impacts such as the hazardous potential of nanoparticles. LCAs seem to be applicable to fewer products and life stages than is needed. Thus, significant gaps in applying LCA to nano give further reason to avoid solo use. In any case, LCAs will need to somehow consider “specific human health impacts and risks with nano-based products in all the (product) life stages such as premanufacture, manufacture, packaging and transport, use, recycling and disposal.” It is possible that only the more limited version of LCA, Life Cycle Inventory, is feasible for near-term use without retooling and rethinking.

In conclusion, LCA’s familiarity is useful for building industry-academia partnerships and identifying practical short-term management options, but is insufficient for upstream management of a new technology before it is well established or quantified. The kinds of questions associated with LCA decision-making are rooted more in a modeling of systems with existing flows insofar as they can be modeled, understood, predicted and acted upon, thus, also illustrates the need for more comprehensive and contemporary EMFs.

D. Waste Equals Food (Cradle to Cradle or C2C) 

C2C is a design protocol that incorporates a code of correct conduct for design. It is the culmination of the partnership of William McDonough, a designer of buildings and products, and Michael Braungart, a green chemist. At its core is the notion that the very concept of waste should be eliminated in industrial design. Every process should be designed so that the products designed, as well as leftover chemicals, materials, and effluents become “food” for other processes, given a dichotomy: technical nutrients and organic nutrients. Every product should be exclusively of one type of “nutrient” or the other, or at least easily separable into distinct parts that are exclusively one type. Organic nutrients become fertilizer in biological applications while technical nutrients consist of materials for continuous reuse/manufacture without degradation, defined as “upcycling.” Whether this is limited by entropy is unclear.

C2C stipulates explicitly that energy should come only from “current solar income” or, preferably, to not use more energy than one generates. Firms should “respect diversity” by predicting impacts on plants, animals, and humans by weighing shorter and longer term effects and whether it “enhances people’s identity, independence, and integrity”. In fact, the nutrient dichotomy raises an interesting question: is it possible that nano itself is unnecessary? Assuming that indeed, a C2C economy is our optimal long-run, is it conceivable that our major concern would not so much be pushing the boundaries of technology but rather learning how to make do with all of the “nutrients” we already have and need and simply determining how to better cycle them? Thus it is vital that a dialogue on the place and purpose of nano in a sustainable future is undertaken, C2C or not.

Insofar as C2C is more demanding than other EMFs, there might be significant short run economic costs. However, achieving a best case long run environmental scenario may require such explicit planning of how we will get from the incremental progress to the bigger prize. Thus, any chosen EMF should directly encourage firms to take greater financial risk or return horizons. C2C advocates moral imagination through optimal organizational behavior.

For technical criteria, C2C is perhaps too narrow in the sense that it focuses more on product design than elsewhere such as how human political and socio-economic systems couple with natural ones a la ESEM. Though nano might require more of a “product focus”, nanomaterials break the mold of what is considered a product. In fact, the breadth of applications means that while Trimetaspheres may be a component in a particular product, they may also be used as a stand-alone chemical, a drug-delivery agent, a lubricant, and other uses where “product” makes a poor descriptor. Plus, the entire supply chain associated with the industries for this material need examining. Yet, C2C’s preexisting variety of sources that developed around it that might help in technical adoption, such as the 200-page book “Cradle to Cradle” and the for and non-profit consulting firms that specialize in it. On the other hand, vagueness may result from a lack of engineering-friendly guidelines with built-in scalability like 12P’s. Thus, the role of data in the design and decision making process becomes ambiguous.

Examining socio-cultural criteria, C2C’s notions of respecting diversity and using local resources indicate that stakeholders’ values are well included. In fact, given the previously discussed irrational fear and exuberance about nano, a socially positive EMF might help provide contextual basis for both their concerns. And since it lacks ideology outside of simple humanist concern, cultural acceptability and portability would seem to be high. However, because the C2C vision is revolutionary compared to what exists today, it conceivably could intimidate entrenched interests, though ideally only slow, not stop adoption.

C2C is a sweeping take on sustainability. Its detailed “normative” (best-case) scenario allows highly positive discussions on not only the how but the why of design choices. Knowledge of direction justifies certain decisions and trade-offs enabling longer-term goals. Just as modularity in sustainable products eases upgrade, EMFs must also consider the ultimate destination and be modular to rapidly adapt to change. Organic/technical cycling differentiates
crucially, yielding more productive goals for ultimate fate of goods. Many firms design for ease of separation, but C2C nutrient cycling demands even greater foresight. One danger though is if firms reason that conforming their technical metabolism to C2C absolves further efforts. Thus, if the materials in their technical cycle are highly toxic they may still qualify though clearly be operating in an unsustainable way. Among C2C’s “five steps to eco-effectiveness”, however, the first step is to “get free from known culprits”.

Troublingly, however, C2C fails big in that fullerenes are not organic or technical. Absence in nature, high stability, and use in industrial applications does point to technical. But its proposed usage as an MRI image enhancing substance, or drug delivery payload indicates organic. But there is no known biodegradation pathway, and even if there was it would free toxic metal atoms. So other than some ingenious recovery of this material from the body (magnetism?) the technical nutrient pathway is also obviated. Still, at least in MRI, Trimetaspheres are preferred to the current alternative.

III. CONCLUSIONS AND FUTURE RESEARCH

ESEM is a big step forward for the tenets of sustainability and their relation to other important worldwide goals and associated stakeholders, in a systems framework. However, tremendous short term hurdles remain like ambiguity of technical implementation, specialized expertise costs, and a lack of needed institutional infrastructure. Using quantitative approaches from established tools like LCA may mitigate this and allow concurrent “packaging” of longer-term goals. 12P is strong technically and economically, illustrating how the language of technical management can reduce short run ambiguity. Market incentives: i.e. reduced liability and operating costs could help finance 12P, prove attractive to stakeholders, and reduce resource usage, toxicity, and risks. Even still, the overall short-run picture is fraught with uncertainty regardless of EMF. The fixed nature of nano funding and high R&D costs complicate the economics. 12P’s long-run picture is murky as it lacks the management, policy, and stakeholder elements of other EMFs, like other traditional environmental approaches that rely on technical policy fixes\(^5\), potentially leading to reduced social and other benefits. A normative scenario, and thus, by extension, how nano would fit into it, is not addressed as in ESEM and C2C.

LCA has wide support but lacks standardization. Initial efforts indicate large gaps for nano. LCA has left out the improvement step yielding poorer client decision options. Thus, LCA should be a toolset within the greater scope defined by a more systemic EMF, and so was discussed rather than evaluated. LCA raises important management issues such as developing a “process to evaluate environmental burdens...by energy/ material flows”\(^6\), fate and quantities of raw materials, resource demands in specialized equipment, and balancing high yields with green production; all essential for any EMF.

C2C deeply considers stakeholders by “respecting diversity” bio-culturally. Its humanist focus helps “cultural portability,” though could create “old industry” resistance. C2C ambitiously advances sustainability by demanding all-renewable energy and by positing a normative scenario and providing the methods and motivations for it, encouraging longer-term planning by firms. C2C has fairly wide support but lacks the technical scalability of 12P, creating ambiguity in data/decision making. Its narrower focus on artifact design and breaking the organic/technical nutrient dichotomy creates potentially insurmountable obstacles.

A combined “hybrid” EMF would include technical language similar to 12P, but includes how business, government, and citizens benefit a la C2C. It would leverage existing databases such as in LCA, and also stimulate institutional infrastructure, market incentives, and cross-industry collaboration and integration. A rigorous systemic model of coupled planetary and human systems ties all of this together to be broad enough for wide implementation and flexible enough for the greater constraints specific applications a la ESEM. For later study, though, is whether weaknesses and incompatibilities can be filtered out, or if the hybrid EMF must be nano-specific or just “nano-aware”.

The breadth of issues involved with the environmental management of nano is more important than ranking EMFs. This effort is itself a gap analysis of issues and expectations for managing nano. Other issues include acquiring proprietary data from manufacturers and patent holders in an industry marked by severe intellectual property worries. What regulatory issues should be added to the design and management processes? Which applications should receive more initial focus? Should we emphasize the mechanics of EMFs or the application technology itself? Much of the analysis in this paper is subjective: readers should consult the sources for these EMFs so that a greater consensus on a direction for sustainably managing nano can be built.

Nano needs either centralized or diffuse leadership. Can we balance degrees of freedom and initiative (diffuse) with cross-organizational alignment (centralized)? Indeed, there is work to do before industry is gigantic as can be imagined, and thus imagination, moral and otherwise, and good faith efforts across disciplines and groups is needed; not just good PR. A spirit of leadership is needed in all sectors.

REFERENCES

[7] “Nanotech’s green side: Cutting waste and risk” Smalltimes, 9/15/03.