Integrating science and business models of sustainability for environmentally-challenging industries such as secondary lead smelters: A systematic review and analysis of findings

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Abstract

Secondary lead smelters (SLS) represent an environmentally-challenging industry as they deal with toxic substances posing potential threats to both human and environmental health, consequently, they operate under strict government regulations. Such challenges have resulted in the significant reduction of SLS plants in the last three decades. In addition, the domestic recycling of lead has been on a steep decline in the past 10 years as the amount of lead recovered has remained virtually unchanged while consumption has increased. Therefore, one may wonder whether sustainable development can be achieved among SLS. The primary objective of this study was to determine whether a roadmap for sustainable development can be established for SLS. The following aims were established in support of the study objective: (1) to conduct a systematic review and an analysis of models of sustainable systems with a particular emphasis on SLS; (2) to document the challenges for the U.S. secondary lead smelting industry; and (3) to explore practices and concepts which act as vehicles for SLS on the road to sustainable development.

An evidence-based methodology was adopted to achieve the study objective. A comprehensive electronic search was conducted to implement the aforementioned specific aims. Inclusion criteria were established to filter out irrelevant scientific papers and reports. The relevant articles were closely scrutinized and appraised to extract the required information and data for the possible development of a sustainable roadmap. The search process yielded a number of research articles which were utilized in the systematic review. Two types of models emerged: management/business and science/mathematical models. Although the management/business models explored actions to achieve sustainable growth in the industrial enterprise, science/mathematical models attempted to explain the sustainable behaviors and properties aiming at predominantly ecosystem management. As such, there are major disconnects between the science/mathematical and management/business models in terms of aims and goals. Therefore, there is an urgent need to integrate science and business models of sustainability for the industrial enterprises at large and environmentally-challenging industrial sectors in particular. In this paper, we offered examples of practices and concepts which can be used in charting a path towards sustainable development for secondary lead smelters particularly that the waste generated is much greater outside the industrial enterprise than inside.

An environmentally-challenging industry such as secondary lead smelters requires a fresh look to chart a path towards sustainable development (i.e., survivability and purposive needs) for all stakeholders (i.e., industrial enterprise, individual stakeholders, and social/ecological systems). Such a path should deal with issues beyond pollution prevention, product stewardship and clean technologies.

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1. Introduction

Lead-acid batteries (LAB) represent 88% of apparent U.S. lead consumption (Genaidy et al., 2008). Thus, the recycling of spent LAB is an important endeavor in this industry, particularly, among secondary lead smelters (SLS). Until recently, recycling rates of LAB in the U.S. were obtained from statistics reported by the Battery Council International (BCI). The BCI stated that the recycling rates for lead content in the LAB lifecycle were 93.3%, 97.1% and 99.2% for the 1995–1999, 1997–2001, and 1999–2003 time periods, respectively. These rates suggest that the LAB product lifecycle is almost behaving as a closed loop system.

An exploratory investigation was undertaken by Genaidy et al. (2008) to closely examine the above issue using an evidence-based methodology requiring the development of an integrated model for the computation of recycling rates in the US market. The findings revealed that the recycling rates from the integrated model were around or above 80% from 1999 to 2001 in comparison to the >97% rates calculated by the BCI model. Thereafter, recycling rates dropped by more than 10%. This could be attributed to a number of reasons, including: (1) amount of lead recovered was stagnant; (2) consumption of lead was growing at a 2.25% annual rate, and (3) amount of lead in imported batteries increased at a higher rate than that for exported batteries. Genaidy et al. (2008) concluded that the opportunities for maximizing lead recovery and recycling are centered on the spent batteries left with consumers, mishandled LAB sent to auto wreckers, slag from smelting inefficiencies, and lead lost in municipal waste.

In light of the above findings, a subsequent study by Genaidy et al. (2009) examined one of the aforementioned opportunities in terms of pollution prevention and waste minimization practices; it examined technologies to significantly reduce the amount of lead in the slag generated from secondary lead smelters. An example was utilized to detail the costs and benefits associated with different combinations of practices and technologies. It was concluded that on the basis of clean technologies and practices, it is technically and economically feasible to implement integrated environmental solutions to increase lead recovery and recycling among U.S. smelters.

As such, we sought to contact stakeholders in the U.S. secondary lead smelting industry to discuss the results. It was soon realized that the number of secondary lead smelters dropped significantly from a peak of 250 in 1980–50 in 1995 and 21 in 2006, respectively. Genaidy et al. (2008) argued that the drop in LAB recycling rates may be explained by the fewer recycling facilities, which may have reduced the number of recycling channels available to capture lead scrap. Alternatively, consolidating lead production may also have the effect of making production more efficient via economies of scale and more focused scrutiny from regulatory agencies. However, one can still question whether an environmentally-challenging industry such as secondary lead smelting is truly sustainable. An extreme example can also support this point such as the discovery of an alternative for lead use in batteries and other applications despite 100% LAB recycling and zero emissions from SLS. This initiated the research efforts reported in this paper as we hypothesized that the issues go beyond pollution prevention and clean technologies.

The primary study objective was to explore whether a roadmap for sustainable development can be established for SLS. The following aims were established in support of the study objective:

- **Aim 1**: To conduct a systematic review and a critical appraisal of existing models of sustainable systems;
- **Aim 2**: To document the challenges for the U.S. secondary lead smelting industry;
- **Aim 3**: To explore practices and concepts which act as vehicles for SLS on the road to sustainable development.

2. Methods

2.1. Search strategy and inclusion criteria

The target subject in this systematic review is the sustainable enterprise. The primary electronic search of databases was conducted in support of Specific Aims 1 and 3 with the following keywords: sustainable (or sustainability), environmental (or environment), social, economic (or economical), and model (system, enterprise, organization, or business). Initially, an examination of source articles was conducted in general search engines including Google and Yahoo to identify the most appropriate databases for the primary electronic search. Academic Search Complete, Business Complete, Environment Complete, and Computer and Applied Science Complete were identified as the most pertinent databases for use in the primary electronic search.

The search process started on December 17, 2008 and concluded on January 6, 2009. Only studies published in English were used. Abstracts and review articles were not included. On the basis of the search, only management models of sustainability were identified. This prompted another electronic search for science/mathematical models.

To augment our electronic search for management models, all online articles published in Harvard Business Review between 1990 and January 2009 were investigated for any additional models. Initially, titles were reviewed, then, full articles of relevance to the target subject were retrieved for further examination. Research articles deemed important were included in the systematic review. In addition to the electronic search, the list of references in review articles and bibliographies of research articles produced from the electronic search were examined for further papers.

A refined search was conducted for science/mathematical models in electronic environmentally-related journals (e.g., Environmental Science and Technology, Science of Total Environment) with sustainability as the general keyword. The bibliographies of identified articles were also searched for additional resources. The electronic and manual search process was conducted in January and February 2009. Only studies published in English were used.

2.2. Data/information extraction, management and analysis

In support of aim 1, the identified management and science models were extracted from the original sources and are documented in Table 1. The description of evidence was presented separately for management/business and science/mathematical models. An analysis of the gathered information is discussed within the context of the sustainable enterprise with an emphasis on environmentally-challenging industries such as the lead smelting industry. To demonstrate the challenges and opportunities facing SLS, an example was documented for a large producer in the SLS industry to address aim 2. To achieve aim 3, we offered concepts which can be utilized in charting a roadmap for a sustainable path for secondary lead smelters.

3. Results

3.1. Identification of studies

Two types of models emerged from the systematic review: management/business and science/mathematical models. Although the management/business models explored actions to achieve sustainable growth in the industrial enterprise, science/mathematical models attempted to explain the sustainable behaviors and properties of ecological systems and, in other
instances, ecological-economic systems. In few cases, management models examined the behaviors of sustainable systems.

The primary electronic search identified articles dealing with management and business models. Fifteen articles were retrieved and reviewed for relevance to the study objective (Holland, 1999; Stead and Stead, 2000; Michelini and Kovacs, 2003; Wustenhagen, 2003; Epstein and Roy, 2003; Hart and Milstein, 2003; Kijak and Moy, 2004; Pope et al., 2005; Lehmann, 2006; Hileman et al., 2006; Young and Tilley, 2006; Petrie, 2007; Mahler, 2007; Cabezas-Basurko et al., 2008; Peon-Escalante et al., 2008). Two studies were deemed relevant, that is, Hart and Milstein (2003) and Young and Tilley (2006). The secondary electronic search yielded the following articles: Porter and van der Linde (1995), Hart (1997), Magretta (1997), Reinhardt (1999), Lovins et al. (1999), Holliday (2001), and Unruh (2008). Additional studies were obtained via bibliography search: Cabezas et al. (2005a, 2005b, 2007), Cabezas et al. (2003, 2005a, 2005b), Shastri et al. (2008a, 2008b), Shastry and Diwekar (2006a, b), Porter and van der Linde (1995), Hart and Milstein (2003), Shrivastava, 1995; Gladwin et al., 1995; Tilton, 1996). A brief synopsis of the description is provided for both model types in Table 1.

3.2. Description of evidence for sustainable enterprise models

The description of evidence is provided separately for the management/business and science/mathematical models. Our model classification is in line with the views reported by other researchers (Porter and van der Linde, 1995; Shrivastava, 1995; Gladwin et al., 1995; Tilton, 1996). A brief synopsis of the description of evidence is provided for both model types in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Type of model</th>
<th>Source</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jennings and Zandbergen (1995)</td>
<td>A model showing the relationship between the firm and ecosystem</td>
</tr>
<tr>
<td></td>
<td>Hart (1997)</td>
<td>Enterprise is the unit of sustainable world and technology in the driver for sustainability</td>
</tr>
<tr>
<td></td>
<td>Magretta (1997)</td>
<td>Strategies can be achieved via pollution prevention, product stewardship, and clean technology</td>
</tr>
<tr>
<td></td>
<td>Hollliday (2001)</td>
<td>The need for sustainability vision</td>
</tr>
<tr>
<td></td>
<td>Cabezas-Basurko et al. (2008)</td>
<td>Substituting material products with information and services</td>
</tr>
<tr>
<td></td>
<td>Lovins et al. (1999)</td>
<td>Three-part strategy: (a) integrating science uniting chemistry, biology and other sciences to develop efficient and environmentally-friendly processes and products; (b) creating value via knowledge; (c) shift productivity improvement from operational to strategic level</td>
</tr>
<tr>
<td></td>
<td>Unruh (2008)</td>
<td>Sustainability metric based on shareholder value-added</td>
</tr>
<tr>
<td></td>
<td>Porter and van der Linde (1995)</td>
<td>Varied approaches: (a) environmental product differentiation; (b) managing competition; (c) cost savings; (d) managing environmental risk; (e) redefining markets; (f) beyond all—or—none approach</td>
</tr>
<tr>
<td></td>
<td>Hart and Milstein (2003)</td>
<td>Four major business practices: (a) increase productivity of natural resources; (b) shift to biologically-based production models; (c) move to solution-based business models; (d) reinvest in natural capital</td>
</tr>
<tr>
<td></td>
<td>Young and Tilley (2006)</td>
<td>Three rules: (1) use a parsimonious palette; (2) cycle up virtuously; (3) exploit the power of platforms</td>
</tr>
<tr>
<td>Science</td>
<td>Shastri and Diwekar (2006a, b)</td>
<td>Link between environment, resource productivity, innovation and competitiveness</td>
</tr>
<tr>
<td></td>
<td>Shastry and Diwekar (2006a, b)</td>
<td>Sustainable value integrated with shareholder value framework</td>
</tr>
<tr>
<td></td>
<td>Shastri et al. (2008)</td>
<td>In line with Holliday (2001) and Shapiro (Magretta, 1997)</td>
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<td></td>
<td>Graedel and Klee (2002)</td>
<td>Comprehensive sustainable entrepreneurship mode</td>
</tr>
<tr>
<td></td>
<td>Anastas and Zimmerman (2003)</td>
<td>Objective stated in terms of Fisher Information index</td>
</tr>
<tr>
<td></td>
<td>Fiksel (2003)</td>
<td>Bottom-up control provided more stable solution; increasing per capita consumption more critical than population explosion; non-domesticated compartments may lead to undesirable consequences if ignored</td>
</tr>
<tr>
<td></td>
<td>Mihelic and Kovacs (2003); Prabhal and Ramaswamy (2003); Shonnard et al. (2003); Tilton (1999)</td>
<td>Use of moving target for sustainable rate</td>
</tr>
</tbody>
</table>

Jennings and Zandbergen, 1995; Shrivastava, 1995; Gladwin et al., 1995; Porter and van der Linde, 1995; Reinhardt, 1999; Lovins et al., 1999; Unruh, 2008) and (b) business executives (Magretta, 1997; Holliday, 2001). The following is an account of the above mentioned contributions:

- Hart (1995) challenged management theory on the grounds that a resource-based view of the firm ignores the constraints imposed by the biophysical or natural environment. Therefore, he advocated the natural resource-based view of the firm that advances strategy and competitive advantage rooted in capabilities which facilitate environmentally sustainable economic activity.

- Jennings and Zandbergen (1995) extended Hart’s arguments via a simple model of the firm which presents its relationship with the ecosystem. According to the authors, sustainability is achieved when: (a) resource extraction from the ecological system occurs within the carrying capacity or sustainable yield of the resource base and (b) waste transfer to the physical components of the ecological system does not exceed their assimilative capacity.

- Hart (1997) built upon his earlier work by reasoning that the total environmental burden created by human activity is a multiplicative function of population, affluence (a proxy for consumption), and technology (a proxy for how wealth is created). Because the stabilization or reduction of the environmental burden is required to achieve sustainability, Hart determined that the first two factors are difficult to control and one is only left with changing the technology to achieve the stated goals. Three strategies were outlined which make up the ‘Sustainability Portfolio’ (i.e., pollution prevention, product stewardship and clean technology).

- Shrivastava (1995) presented a blueprint for four corporate actions for ecologically sustainable development which has some degree of overlap with the Hart’s framework. He maintained that total quality environmental management and ecologically sustainable competitive strategies are easier to implement because their elements are under corporate control. Technology transfer requires some government involvement and controlling population is even further outside the sphere of corporate influence.

- Gladwin et al. (1995) suggested the unification of the technocentric and ecocentric paradigms to form the sustainable paradigm. Gladwin and co-workers proposed eight operational principles and corresponding techniques of biophysically sustainable behavior to achieve their research goals.

- In an interview by Magretta (1997), Shapiro, the CEO of Monsanto, echoed Hart’s arguments with technology as the driver for global sustainability. He reasoned that a closed loop system like the earth cannot support an unlimited increase in material things but it can support an exponential increase in information and knowledge. Therefore, Monsanto explored ways to substitute information for “stuff” and services for products. For example, the company genetically coded plants in its agriculture business to destroy harmful insects. In another example, Monsanto determined on the basis of carpet recycling economics that if the manufacturer owns the carpet and leases it to customers, it may be feasible to put more cost up front and make the carpet more recyclable. In this respect, Monsanto examined the lifecycle of all its products and questioned whether people really need to buy stuff or need services. The aforementioned logic seems ingrained in the compatibility between sustainability and development on the basis of creating value and satisfying people’s needs by increasing the information component of what is produced and diminishing the material component.

- In line with Hart’s arguments and Shapiro’s practices, Holliday (2001), the CEO of DuPont, adopted a three-part strategy for action to fuel sustainable growth: (a) Integrated science unifying chemistry, biology and other sciences to develop processes and products that are efficient and environmentally friendly; (b) Creating value via knowledge intensity by adding more knowledge content into products and services; and (c) Elevating productivity improvement from an operational level to a more central strategic level. To monitor their progress towards a more sustainable enterprise, DuPont has created a metric for this purpose that is termed shareholder-value-added (SVA) per pound of production, defined as the shareholder value created above the cost of capital. Holliday reasoned that, the greater the knowledge intensity in creating economic value, the higher the shareholder value added per pound of production.

- Reinhardt (1999) emphasized that managers should address environmental problems as business issues through one or more of the following: (a) environmental product differentiation (although such efforts may increase the costs of business, one can still command higher prices, capture additional market share, or both); (b) managing competition (although a company may incur higher costs to respond to environmental pressure, it can still come out ahead if it forces competitors to raise their costs even more); (c) cost savings (some organizations are able in some situations to cut costs and improve environmental performance); (d) managing environmental risk (effective management of environmental risk can be a competitive advantage by avoiding the costs of industrial accidents or environmental lawsuits); (e) redefining markets (companies are rewriting the competitive rules in the markets, for example, Xerox redefined their business model by not only selling office equipment, but also, containing responsibility for the equipment’s disposal and taking back the products from consumers when superseded by new technology, with the machines disassembled, remanufactured and resold at the same price as new technology); and (g) beyond all-or-nothing approach (by exploiting the environment as a business issue, imaginative and capable managers will find unlimited opportunities).

- Lovins et al. (1999) argued that industries only considered the exploitable resources of the earth’s ecosystems (e.g., oceans, forests) and did not take advantage of the larger free services that those systems provide. For example, forests not only produce wood fibers, but also provide services such as water storage and habitat. In this respect, Lovins et al. advocated four major shifts in business practices: (a) to dramatically increase the productivity of natural resources; (b) to shift to biologically inspired production models (natural capitalism seeks to eliminate the concept of waste); (c) to move to a solution-based business model — (e.g., providing illumination rather than selling light bulbs); and (d) to reinvest in natural capital. Indeed as human needs increase, higher costs are accrued as a result of deteriorating ecosystems resulting in the greater environmental awareness of consumers.

- Unruh (2008) outlined three rules derived from the biosphere’s operating system: (1) Rule 1 — use a parsimonious palette: nature uses four (carbon, hydrogen, oxygen and nitrogen) out of more than 100 elements to produce all living things; (2) Rule 2 — cycle up virtuously: Standardization ensures that raw materials are always available to the organisms (i.e., they do not have to be shipped or sorted); and (3) Rule 3 — exploit the power of platforms, with a general-purpose design platform used to create the planet’s biodiversity.
• **Porter and van der Linde (1995)** rejected the static view that there is a fixed trade-off between ecology and economy. They maintained that properly designed environmental standards can trigger innovations which can lower the total cost of a product or improve its value. Such innovations allow companies to use a range of inputs more productively, thus, offsetting the costs of improving environmental impact and ending the stalemate.

• **Hart and Milstein (2003)** expanded Hart’s earlier work (1995, 1997) to establish a sustainable value framework in line with arguments made by the CEOs of DuPont (Holliday, 2001) and Monsanto (Magretta, 1997). They maintained that industrial managers are still having difficulty addressing corporate sustainability; hence, they reasoned that managers should directly link enterprise sustainability to the creation of shareholder value. Hart and Milstein view shareholder value as a multi-dimensional construct confirming the DuPont and Monsanto viewpoints (Holliday, 2001; Magretta, 1997). Young and Tilley (2006) presented a comprehensive sustainable entrepreneurship model that integrates several of the aforementioned models (e.g., operational principles of Gladwin et al., 1995) as well as the corporate sustainability work of Dyllick and Hockerts (2002) and McDonough and Braungart (2002).

### 3.2.2. Science/mathematical models

Cabezas and Fath (2002) proposed a sustainability hypothesis on the basis of the Fisher Information Index which estimates a parameter as the amount of information that can be extracted from a set of measurements or as a measure of the order of a system, with the latter interpretation as the basis in their formulations. The sustainability hypothesis suggests that the Fisher Information index does not change with time for a system in a sustainable state. In addition, they maintained that (1) if Fisher Information increases with time, the system shifts to a different sustainable state in the direction of increasing self-organization; and, (2) if Fisher Information decreases with time, the system is losing its state of self-organization (that is, the system is dying or ceasing to exist). Cabezas and Fath maintained that self-organization is a critical and necessary property of living functioning systems. The sustainability hypothesis and its corollaries were demonstrated using a two-species predator-prey Lotka-Volterra model. Cabezas et al. (2003) applied their work to a 12-compartment model representing a social system that regulates the flows of mass according to its own criteria. The results showed that Fisher Information is a sensitive measure of the variability in the steady state regime of a dynamic system and confirmed their sustainability hypothesis. Cabezas and colleagues pointed out that their model is only applicable to dynamic systems in a cyclic steady state. Cabezas et al. (2005a, 2005b) further explored the 12-compartment model for different scenarios in which an industrial process was added to the framework. Their earlier assertions about the Fisher Information Index were still valid. The updated 12-compartment model was further investigated in Cabezas et al. (2007) where a price-setting macro-economic model regulating some compartments was employed. The results were useful in providing interpretations for different scenarios emulating a mini-world representation of human industrial activities.

The limitations of the models employed in Cabezas et al. (2005a, b, 2007) were addressed by Shastri et al. (2008a,b) using optimal control theory and dynamic programming. As expected, multivariate control using variables of distinctly different nature was shown in Shastri et al. (2008a) to be more effective than uni-variate control. In essence, the control of factors at the base of the food chain is more critical than attempting modifications towards the high end of the food chain. Changes in the industrial and human sectors cannot alter the basic natural resource consumption patterns. Shastri et al. (2008b) further improved the parameters and their initial values in the original ecological-economic model of Cabezas et al. (2007). It was found, for example, in their updated model that the increasing per capita consumption of resources is more critical than population explosion. Furthermore, undesirable developments in the non-domesticated (i.e., wild) compartments were often overlooked by typical economic observations and may lead to sudden disasters if ignored. When the Fisher Information was used as an indicator of sustainability, economic parameters emerged as better predictors of instability. The result also showed that a waste discharge fee, individually and in combination with other control variables, is effective in delaying but not eliminating instability.

The detailed formulations of the aforementioned control models were outlined in Shastri and Diwekar (2006a,b). They maintained that an ecosystem is possibly regulated via top-down or bottom-up control. Thus, their work compared the two control philosophies using the optimal control theory for a population growth model (i.e., three-species predator-prey model) in an ecosystem using sustainability as the objective which is quantified by the Fisher Information. In Shastri and Diwekar (2006a), deterministic models were employed to formulate the control profiles. It was observed that although the top-down control was aggressive with regards to ecosystem management, it could result in instability; conversely, the bottom-up control provided a stable and improved dynamic response. The results also indicated that the bottom-up control was a better option to affect shifts in the dynamic regimes of a system which could be required to recover the system from natural disasters. In Shastri and Diwekar (2006b), analysis of the deterministic system was performed with the incorporation of uncertainty in the mortality rate of the predator species. When the objective was to minimize the Fisher Information variance, the results agreed qualitatively for both the deterministic and stochastic models. On the other hand, the results differed when the objective was to maximize the Fisher Information with the instability of deterministic models absorbed by the noise introduced by the uncertainty. It was concluded that the degree of uncertainty was important to identify the most appropriate management strategy.

Although the work by Cabezzas and associates was the primary vehicle directed at developing a theory of sustainable systems, a number of other contributions in the environmental science and technology literature are worth mentioning.

• **Graedel and Klee (2002)** developed a simple model in which sustainability (defined here for the rate of use of resources) was identified as a target or a goal. The model consisted of four steps: (a) establish the available supply of resources; (b) allocate the annual permissible supply according to a recent formula or market analysis; (c) establish the recaptureable resource base; and, (d) derive the sustainable limiting rate of use and compare it to the current rate of use. The model utility was demonstrated in three examples employing zinc, germanium, and greenhouse gases. Graedel and Klee concluded that a sustainable rate of resource utilization should be a moving target rather than fixed for all times, hence, recommending the computation of targets every few years while retaining the 50-yr depletion horizon.

• **Marshall and Toffel (2005)** built upon the work of Graedel and Klee (2002) and the frameworks of triple bottom line (Elkington, 1998), natural step (Nattrass and Altomare, 1999), and ecological footprint (Wackernagel et al., 2002) to establish
the sustainability hierarchy in analogy to the hierarchy of needs developed by Maslow (1954). The sustainability hierarchy calls for the most basic needs at the bottom and builds its way up as follows: (a) actions that if continued at the current or forecasted rate endanger human survival; (b) actions that significantly reduce life expectancy or other basic health indicators; (c) actions that may cause species extinction or that violate human rights; and, (d) actions that reduce the quality of life or are inconsistent with other values, beliefs or aesthetic preferences.

- Anastas and Zimmerman (2003) developed twelve principles of green engineering to achieve sustainability through science and technology: (1) all material and energy inputs and outputs should be inherently nonhazardous as possible; (2) prevention instead of treatment; (3) design for separation; (4) maximize mass, energy, space and time efficiency; (5) output-pulled versus input-pulled; (6) conserve complexity; (7) durability rather than mortality; (8) meet need, minimize excess; (9) minimize material diversity; (10) integrate local material and energy flows; (11) design for commercial ‘afterlife’; and (12) renewable rather than depleting.

- Fiksel (2003) identified four properties for sustainable systems: diversity, efficiency, adaptability, and cohesion. He advocated the following steps to encourage the design of sustainable systems (‘design for sustainability’ is defined here as allowing the modifications of controllable characteristics of designed artifacts such as factories and products in ways that create environmental and social benefits): (1) identifying system function and boundaries; (2) establishing requirements; (3) selecting appropriate technologies; (4) developing a system design; (5) evaluating anticipated performance; and, (6) devising a practical means for system development.

- Educators suggest the need to develop meta-disciplines on the basis of sustainability science/engineering and green engineering to inspire knowledge advances with respect to sustainable systems (e.g., Mihelcic and Kovacs, 2003; Shonnard et al., 2003).

Although the efforts of Cabezas et al. were based on the classic population growth model of Lotka-Volterra, we found that Tillman (1999) proposed a mechanistic resource-based ecological model. A central feature of this model is the exclusion principle which states that, in the context of a multi-species competition for a limiting factor in a patch free of disturbance, the species with the lowest resource requirement in equilibrium will competitively displace all other species. Brock and Xepapadeas (2002) expanded the Tillman’s model into an ecological-economic model for ecosystem management. They analyzed the equilibrium state resulting from nature’s equilibrium with two basic management problems (i.e., privately optimal management and the socially optimal management).

3.3. Analysis of findings and determinants of sustainable enterprise

Analysis of management and business models suggests the following:

- Knowledge is becoming a competitive advantage for industrial enterprises (e.g., Magretta, 1997; Holliday, 2001). It should be used as one of the drivers for, among other things, value creation by the enterprise.

- Value creation should be better articulated for individual shareholders as well as economic and social-ecological systems (e.g., Holliday, 2001; Hart and Milstein, 2003; Young and Tilley, 2006).

- Principles of natural processes and production should be adopted for business development and practices (e.g., Lovins et al., 1999; Unruh, 2008).

- Multiple strategies should be embraced in creating improvement actions for the sustainable enterprise (e.g., Shrivastava, 1995; Hart, 1995, 1997).

- Environmental regulation should be in harmony with the role of value creation in the sustainable enterprise (Porter and van der Linde, 1995).

- An integrated model is needed to synthesize the different views expressed in the published literature. Although there are areas of overlap among the different models, there are also areas of uniqueness. We can benefit from piecing together commonalities and areas of uniqueness into the integrated model which can be applied in practice and evaluated in longitudinal studies to determine the short and long term impacts.

Analysis of science and mathematical models of sustainable systems reveal the following:

- A hierarchy of needs was recommended as a framework for sustainable development which is in line with the hierarchy of needs established for social systems (Marshall and Toffel, 2005).

- The characteristics and technical principles were established for sustainable systems (Fiksel, 2003; Anastas and Zimmerman, 2003).

- Ecosystem management depends on the degree of interplay between bottom-up and top-down methods of control (Shastry et al., 2008a, 2008b; Cabezas et al., 2005a, 2005b, 2007).

- A sustainability hypothesis and corollaries was put forward and defined in terms of Fisher Information (Cabezas and Fath, 2002).

- The mathematical representation of the sustainable enterprise has yet to be established for the industrial organization. Indeed, the interaction of models of resource competition (e.g., Tillman model) and predation (e.g., Lotka-Volterra model) should be explored to develop the best strategies for working towards the sustainable enterprise.

- The suggested integrated management model can support the efforts of science models. In this respect, one should take into account the joint optimization of environmental, economic and social dimensions of sustainability.

In light of the systematic review and analysis of findings, one may ask ‘what constitutes the architecture of sustainable enterprise?’ Parrish (2007) attempted to address parts of this question via the identification of two organizing principles and a macro model for the sustainable enterprise (Fig. 2).

- The first organizing principle calls for the harmonization of value (i.e., something that contributes to the system’s existence) of enterprise activities among hierarchical levels (i.e., stakeholder or lower level, enterprise or current level, socio-ecological or higher level). In this respect, value to individual stakeholders takes two forms: (a) relations allowing the satisfaction of basic and social needs; and (b) relations allowing people to contribute to surrounding systems in meaningful and creative ways. Value to the enterprise is centered on: (a) relations that maintain the perceived inducement-contribution balance in sufficient ways; and (b) relations promoting the enterprise’s capacity for value creation. Value to the socio-ecological system consists of: (a) relations contributing to ecologically and socially sustaining functions (e.g., use of
ecosystem resources must not exceed their rate of regeneration, waste emissions must not exceed the ecosystem assimilative capacity, use of non-renewable resources must not exceed development of renewable substitutes, maintaining functional diversity in a certain range).

- The second organizing principle emphasizes the harmony of survival (e.g., sustainability for social-ecological system) and purposive (e.g., qualitative improvement of social-ecological systems) values. Parrish argued that a successful sustainable enterprise is one which fulfills both principles such that the process and outcome of its activities contribute to both the survival and realization of purpose at multiple hierarchical levels (i.e., inside and outside the organization).

By combining the two principles, one can design a model of sustainable enterprise that: (a) both survival and purposive needs are aligned at each hierarchical level, and, (b) the value flow at each level is harmonized with the requirements of higher and lower levels (Fig. 1).

The Parrish architecture is embedded in several of the concepts drawn from our systematic review such as the hierarchy of needs for sustainability. However, it appears to have been developed independently as the great majority of the sources used in our systematic review were not cited by Parrish. This macro-architecture serves as a good platform for developing a quantitative model for sustainable enterprise assessment and management. The principles of harmonization can then be translated into compatibility functions as coined by Genaidy et al. (2009). After discussing the challenges and opportunities for SLS in the next section, the aforementioned issues will be discussed in the formulation of a roadmap for sustainable SLS.

3.4. Challenges for SLS

Fig. 2 depicts an industrial organization within the framework of economic, social and ecological systems (modified from Tyteca, 1999). Table 2 provides examples of the inputs and outputs to all three systems for a large secondary lead smelter in the US, producing 140,000 tons per year from spent lead acid batteries. The dual ecological and economic pressures from wasted lead product include the amount of lead lost in slag, which is approximately 1023 tons on an annual basis. Furthermore, the amount of fugitive elemental lead dust is about 3.15 tons.

It is well documented that lead pollutants and waste are a primary threat to ecological and social systems impacting both environmental and human health. In a study by Palacios et al. (2002), horses were diagnosed with lead poisoning on farmland in the vicinity of a battery recycling plant on the basis of clinical signs and laboratory findings. Lead intake indicated the ingestion of lead from vegetation growing in sites closest to the recycling plant and was approximately 99.5 mg Pb/kg body weight/day surpassing the fatal dosage for horses of 2.4 mg Pb/kg body weight/day. Another study by Liu (2003) found similar findings among sheep and horses living on farmland in the vicinity of non-ferrous metal smelters. The amounts of lead found were 6.0 and 21.4 mg Pb/kg body weight/day, respectively, for horses and sheep; this surpasses the fatal dosage for these animals by several-fold.

An investigation of lead from atmospheric pollution by Kalas et al. (2000) found concentrations of lead in the livers of willow grouse (Lagopus lagopus), black grouse (Tetrao tetrix), and hare (Lepus timidus) in samples collected from 77 locations across Norway. Strong positive relationships were found between lead in livers and atmospheric deposition of lead for all species and age groups studied. The authors deduced that long-range atmospheric transport was the main source of lead in the animals studied.

With respect to the social system, Hiles and Walker Guevara (2006) reported that 56% of children living within a ¼ mile of a large US secondary lead smelter had high blood lead levels. Furthermore, the secondary lead smelter paid more than $10 million for the relocation of residents around the production facilities, as well as, additional millions of dollars for the clean-up of the contaminated areas. Due to the more restrictive environmental regulations in the US, the same large US secondary smelter started to operate a large facility in Peru with history repeating itself, only on a larger scale.

Further support to the social system comes from de Freitas et al. (2007) in which 311 of the investigated 850 children living near a battery recycling plant had blood lead levels (BLL) above the action limit established by the World Health Organization. Risk factors identified for BLL were: living in unpaved areas, parents working in the plant, distance from the plant, playing on the ground, and drinking locally produced milk. Bellinger (2004) suggested that the effect of lead on the central nervous system of children seems to be irreversible. Tong et al. (2000) emphasized that, although acute lead poisoning among humans is becoming rare in developed countries, chronic exposure to low levels of the metal is still a public health issue.

In addition to lead waste, emissions of other pollutants are sizable. As shown in Table 2, a typical operation of a large secondary lead smelter (producing 140,000 tons of lead) may result in land and air emissions in the order of tons (e.g. land emissions of 295.5 tons of antimony, 18 tons of cadmium, 60.4 tons of arsenic; and air emissions of 2524 tons of SO₂ and 6.86 tons of particulate matter). These amounts are far in excess of those which can be...
found in non-contaminated areas. For example, Borovicka et al. (2006) reported that smelting operations cause distinctively elevated concentrations of antimony (1–100 mg/kg) in macro-fungi relative to those in clean areas (<100 µg/kg). With respect to inputs, the operation consumes a great deal of energy (about 196 MW per year) and raw materials (e.g., 7757 tons of coke; 6346 tons of iron).

There are also financial burdens imposed on the secondary lead smelter to attempt to reconcile the ecological and social burdens outlined above. For example, a smelting facility is required to obtain multiple permits at the state and/or federal levels with restrictions on the amount of air and land emissions. Multi-million dollar financial assurance obligations to clean-up potential future contamination are typically required as part of the permitting process. Any environmental violation in such an industry is also met with severe financial burdens. In sum, the environmental costs of permits and violations for a large smelter are usually in the order of several million dollars at a minimum.

From the above example, one can deduce that there is a significant amount of waste produced from a typical large secondary lead smelter. Based on current knowledge, the social and ecologic systems in the immediate vicinity of the secondary lead smelter are at the greatest risk of contamination. From a regulatory standpoint, although there is a mandatory monitoring of emissions around the smelter facilities, discovery of contamination may come many years later.

In addition to the above, Moors and Mulder (2005) pointed out other barriers which may impact sustainability for SLS particularly in the face of implementing newer technologies. A primary barrier is the lack of strong knowledge infrastructure for the medium- to small-size smelters as typified by the small R&D personnel mainly utilized in troubleshooting and process optimization, hence, they lack the expertise for implementation of new technologies and associated best practices. The organization and culture of the firm may act as an impediment towards adopting newer technologies as well as the degree of success in circumventing drastic government regulation. In addition, many of the lead products put on the market such as lead acid batteries remain unclaimed from among customers.

3.5. Path toward sustainable SLS

In search for opportunities for lead recovery and recycling in the US market, Genaidy et al. (2008) found the following results along the trajectory of lead–acid battery lifecycle: (1) lead content in spent batteries with consumers (140,146 tons/year), (2) mishandled LAB sent to auto salvage residue (8573 tons/year), (3) slag generated due to the inefficiencies of lead recycling technologies (8580 tons/year), and (4) lead lost in municipal waste (150 tons/year). That is, the lead content in spent batteries with consumers account for almost 89% of the lead in the environment. On the other hand, the slag resulting from process inefficiencies and ineffectiveness, although substantial in terms of quantities and has major impact upon the environment as demonstrated in the previous section, accounts for only 5.5% of the lead in the environment. As such, it is quite evident that the issue at hand goes outside the walls of the SLS enterprise and beyond clean technologies. Not only this issue requires a major transformation of the corporate mindset into one associated with the learning organization to benefit from the experience of the self and those of others, but also, partnerships among the various stakeholders to achieve viable solutions meeting everyone’s needs.

With the above in mind, we hypothesize that a sustainable industrial enterprise leads to a sustainable society. In other words, it is a necessary condition but not sufficient by itself because of the multitude of stakeholders involved in the issue at hand. Shin et al.
(2008) recognized this issue and argued that “a sustainable society can be assumed to be a society which consists of a sustainable production system, a sustainable community, a sustainable ecosystem and a sustainable government”. Collectively, these elements are necessary to achieve the goal of a sustainable society particularly in the case of lead-based products in which lead is the most toxic substance in the US. Although it is beyond the scope of this article to find solutions for this formidable issue, we offer the following practices and concepts for consideration to chart a path towards a sustainable SLS enterprise and community. The concepts are built around both external and internal forces impacting the industrial enterprise (Gouldson, 2008).

- Lehmann (2006) described the ‘Green Network’ experience in Denmark which was built on the rocks of public – private partnerships. In this concept, a distinct partnership mode of government – business relationships was initiated on the basis of a collaborative network with respect, trust and mutual legitimacy as its tenants. According to Lehman, it is concluded that ‘public – private partnerships can become useful vehicles in societies’ move towards sustainability. A primary lesson learned from this national experience is that one can move from the command and control attributes of regulatory entities towards a green-based, goal-oriented regulatory entity in which the industrial enterprise and regulatory governmental systems work in harmony together to achieve the goals of a sustainable society.

- Government – private partnerships may facilitate the adoption of clean technologies by the industrial enterprise. Moors et al. (2005) pointed out that economic barriers are a major constraint in adopting clean technologies. Kemp and Volpi (2008) described the diffusion process of adopting technologies processes can be long. Thus, investment in the long term goals of the sustainable industrial enterprise may require new collaborative partnership efforts among the government, financial institutions and industrial enterprises to make loans affordable to the industrial enterprise to achieve its goals. In this regard, researchers (e.g., Jain, 2007) even suggested the adoption of approaches such as government subsidies to remove impediments and facilitate implementation of clean technologies. In addition, knowledge collaboration between government researchers and stakeholders in the industrial enterprise can be useful vehicles to facilitate the diffusion of clean technologies in industrial enterprises.

- The architecture of the industrial enterprise should be fundamentally changed to move towards the era of sustainable production in its truest sense. As eloquently stated by Keijzers (2002), the sustainable enterprise is “about business processes that not only curb polluting emissions, and endure re-use or renewable and recyclable resource stocks, but also allow for the preservation of the key stocks of natural capital, while at the same time allowing for adequate social and economic development”. One possible element of this architecture is ‘servicing’, that is, an entity built upon the notion that people want services, not necessarily stuff as voiced out by leading companies such as DuPont, Monsanto and Xerox. This may be beneficial for environmentally-sensitive industry which deals with products based on toxic substances.

- The principles of a sustainable enterprise are long term in nature. With this in mind, one should develop, in addition to the aforementioned architecture, a battery of indicators and metrics to allow the firm to monitor its own progress along the path of sustainability as well as in reference to other enterprises in its own sector and the industry at large. In this regard, one can be guided by the work of, among others, Tyteca (1999), Callens and Tyteca (1999), Krajnc and Glavic (2005), and Young and Tilley (2006). In addition, there is a need for advanced analytics tool which can act as supplemental dynamic and quantitative decision-making tools for the industrial enterprise’s management executive team. Such a tool will move beyond the traditional production function with labor and capital inputs as well as the technical change. As pointed out by Binswanger (1998), such a function should integrate nature into it to compensate for the loss of natural capital and ecosystem services. One should keep in mind that the above mentioned architecture, battery of indicators and metrics, and dynamic quantitative tools should integrate into them the principles of the sustainable enterprise outlined by Parrish (2007) as well as the work of others reviewed in this paper. This issue should go beyond the theory of sustainable systems for ecosystem management as reviewed in this paper and the traditional concepts of pollution prevention frameworks (Hossain et al., 2008; Chaaban, 2001). Emphasis should be based on developing sustainable systems for the industrial enterprise. The works of O’Hara (1998), Sonntag (2000), and Morikza et al. (2006) on sustainable production are useful examples in this regard. All the above issues collectively require the development of the knowledge-based firm within the framework of the sustainable enterprise. Examples from the work of Nemati et al. (2002) and Nonaka (1991) can be useful in this regard.

In summary, the transition to the sustainable enterprise as pointed out by Keijzers (2002) can be complicated and difficult. Furthermore, as advocated in this paper and supported by Shin et al. (2008) a sustainable enterprise is a necessary condition but not sufficient by itself to move towards a sustainable society. Therefore, major efforts should be undertaken at the all levels to protect and promote the new roles of the unit of society and generator of wealth, that is, the sustainable enterprise.

4. Discussion and concluding Remarks

The findings of Genaidy et al. (2008) suggest that the waste produced from lead-acid batteries is much greater outside the industrial enterprise than inside. Furthermore, the number of facilities engaged in recycling and recovering lead has been on the decline over the past three decades. This prompted us to reason out that the issues at hand in the secondary lead smelting industry are beyond pollution prevention and clean technologies. Therefore, we explored approaches to determine whether a path can be charted towards sustainability for this industry.

From the evidence-based methodology reported herein, two types of models emerged: management/business and science/mathematical. The management/business models explored actions to achieve sustainable growth in the industrial enterprise. For example, Gladwin et al. (1995) reported operational principles and techniques of biophysically sustainable behavior. Shrivastava (1995) documented an inventory for corporate actions which are geared towards ecologically sustainable development. Hart (1995) provided a resource-based framework for corporate sustainable production. Collectively, the different efforts were geared at the development of parts of the whole (that is, sustainable enterprise). No attempt has been made to provide the blue prints for the sustainable enterprise’s architecture. On the other hand, the science/mathematical models attempted to explain the behaviors and properties of sustainable systems such as simple economic-ecological systems with the predominant goal to manage ecosystems. For example, the works of Cabezas and associates (e.g., Cabezas and Fath, 2002; Shastri et al., 2008a,b) aimed at the development of a theory for sustainable systems with the end goal
how to manage ecosystems. Fiksel (2003) elaborated on the properties of sustainable systems. As such, there are major disconnects between the science/mathematical and management/business models in terms of aims and goals. Therefore, there is an urgent need to integrate science and business models of sustainability for the industrial enterprises at large and environmentally-challenging industrial sectors in particular.

The macro-architecture of Parrish (2007) is a good start to develop the roadmap for the sustainable industrial enterprise. In this paper, we offered examples of practices and concepts which may be considered in charting a sustainable pathway for secondary lead smelters. To achieve this purpose, many issues should be kept in mind. Sustainability is a continuum that extends from survivability to purposive needs. Value creation should be achieved among the different stakeholders, that is, social/ecological systems, industrial enterprise, and individual stakeholders. As such, compatibility should be achieved at all levels. Another important element to consider is the influence of federal and state regulatory systems. As pointed out by Porter and van der Linde (1995), this will bring harmony between enterprise activities and environmental regulations resulting in innovations that can lead to, among other things, the significant reduction of environmental costs and maintenance of the benefits. With the above in mind, it may indeed be possible to develop a sustainable enterprise for an environmentally-challenging industry. However, this is only possible if all stakeholders enter genuine partnerships to move towards the grand goal of a sustainable society as envisioned and theorized by Shin et al. (2008).

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