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Industrial ecology framework for achieving cleaner production in the mining and minerals industry

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Abstract

Industrial ecology (IE) is an emerging framework adopted in the manufacturing, construction, and process industries to provide innovative solutions in strategic planning, leading to cleaner operation and production. An IE framework integrates a large number of processes, economic constraints, and environmental, health and safety considerations for optimized resource utilization. This paper provides a review of environmental management practices in the mining and minerals industry, emphasizing two concepts: IE and cleaner production. The mining and minerals industry provides primary materials for industrial activities; as such, it is an important component in the "industrial ecosystem." This industry is subject to very stringent social and environmental scrutiny, while providing society with required natural resources to meet essential sustainable development requirements. The implementation of an IE framework in the sector will contribute to sustainable development.

Keywords: Sustainable development; Industrial ecology; Cleaner production; Pollution prevention; Waste minimization; Mining operation; Mineral processing

1. Introduction

Industrial ecology (IE) is an emerging field, which covers the study of physical, chemical, and biological interactions and interrelationships both within and between industrial and ecological systems [1]. Implementing an IE framework incorporates the strategy of cleaner production and pollution prevention in industrial activities. The application of IE principles to mining and mineral processing is therefore a logical step. This framework also promotes understanding of the impacts of industrial systems on their environment.

This framework paper addresses two major concepts: (1) IE, and (2) cleaner production for achieving sustainable development (SD) in the context of the mining and minerals industry. Sustainable development and the mining and minerals industry has been the focus of recent academic and industrial research [2], especially the work performed as part of the Mining, Minerals and Sustainable Development (MMSD) project [3]. There have been numerous other recent publications on this topic which focus on the mining and minerals industry specifically, including two compendiums of conference proceedings [4,5]. However, to achieve SD, the highest goal, at the global level, a strategic plan for implementing effective policies for cleaner production and pollution prevention at the corporate and operational levels is essential. Such policies must emphasize waste minimization, recycling, pollution control, and waste disposal activities at the local (operational/site) level. IE provides a framework for synthesizing these concepts at various levels to improve operational efficiencies and reduce the

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negative impacts of industrial activities on the ecological system.

This paper presents a broad framework to implement IE processes in the mining and mineral processing industries at the global/corporate level. It strives to clarify the relationships between IE, cleaner production and pollution prevention. In order to contribute to sustainable development, the industry must successfully implement these activities at the operational level; much of this already occurs. The next section provides a number of definitions; this is followed by sections on the proposed global framework, and cleaner production and pollution prevention.

2. Definitions

This section of the paper provides a selection of definitions of industrial ecology and cleaner production. There is no single definition of industrial ecology (IE) that is universally accepted; a number of definitions are available in the IE compendium [1]. However, the two most authoritative definitions [6] are introduced here for further discussion. They are as follows:

According to Tibbs [7]:

"The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the manmade system, in order to achieve a pattern of industrialization that is not only more efficient, but that is intrinsically adjusted to the tolerances and characteristics of the natural system. The emphasis is on forms of technology that work with natural systems, not against them… Applied industrial ecology is an integrated management and technical program including:

- The creation of industrial ecosystem
- Balancing industrial input and output to natural ecosystem capacity
- Dematerialization of industrial output
- Improving the metabolic pathways of industrial processes and materials use
- Systematic patterns of energy use
- Policy alignment with a long-term perspective of industrial ecosystem evolution."

Graedel and Allenby [8] define IE as:

"… the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a system view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to product, to waste product, and to ultimate disposal. Factors to be optimized include resources, energy and capital."

Both definitions emphasize the interrelationships between natural and industrial systems and the necessity to limit environmental impacts by balancing input, output and ecosystem capacity. This concept can be accepted at the global/corporate level. However, it can also be applied at the local/operational level with the aim of optimizing resources, energy and capital.

Next, the concept of cleaner production (CP) is introduced. CP or CP terminology was introduced by the UNEP [9]. CP is an internationally-accepted term describing processes emphasizing reductions in negative environmental impacts from processes, products, and services, and the implementation of improved management strategies, methods, and tools [10]. In North America, the term Pollution Prevention (P2) is used interchangeably with CP. P2 is similar to CP but tends to be applied almost exclusively to manufacturing processes. CP is therefore more universally acceptable and applicable to industrial processes in general. The UNEP definition of CP [9] is as follows:

"…the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment. Cleaner Production can be applied to the processes used in any industry, to products themselves and to various services provided in society."

The mining and mineral industry includes many production processes and services. The relevant UNEP definitions [9] are as follows:

- "*For production processes*, Cleaner Production results from one or a combination of conserving raw materials, water and energy; eliminating toxic and dangerous raw materials; and reducing the quantity and toxicity of all emissions and wastes at source during the production process."
- "*For services*, Cleaner Production implies incorporating environmental concerns into designing and delivering services."

A definition of P2 is also included for completion. Moreover, this definition is applicable to mining equipment manufacturers as P2 emphasis is on the manufacturing process. The definition is provided in the US CFR 42 [10] as part of the US Pollution Prevention Act of 1990:

"The term "source reduction" [or pollution prevention] means any practice which (i) reduces the amount of any hazardous substance, pollutant, or contaminant entering any waste stream or otherwise released into the environment (including fugitive emissions) prior to recycling, treatment, or disposal; and (ii) reduces the hazards to public health and the environment associated with the release of such substances, pollutants, or contaminants. The term includes equipment or technology modifications, process or procedure modifications, reformulation or redesign of products, substitution of raw materials, and improvements in housekeeping, maintenance, training, or inventory control. The term "source reduction" does not include any practice which alters the physical, chemical, or biological characteristics or the volume of a hazardous substance, pollutant, or contaminant through a process or activity which itself is not integral to and necessary for the production of a product or the providing of a service."

In addition, the EPA "Pollution Prevention Directive" defines P2 [11] as:

"…the use of materials, processes, or practices that reduce or eliminate the creation of pollutants or wastes at the source. It includes practices that reduce the use of hazardous materials, energy, water, or other resources and practices that protect natural resources through conservation or more efficient use."

These definitions are used in this paper as a basis for recommending implementation of an IE framework for mining and mineral processing. The SD concept introduced earlier is well understood in the mining and mineral industry [2,3]. Other concepts such as waste minimization, recycling, pollution control, and waste disposal are now well established and implemented at operational levels.

3. Integrating the concepts

The aim of this section is to synthesize the concepts of CP and P2 from the local/operational level to the global/societal concept of SD by strategy and policy implementation at the global/corporate organizational level through the IE framework. This will provide a platform for systems-based integration of various contributing activities and processes.

Hamner [6] refers to the relationship among key environmental management practice (EMP) terminology (SD, IE, CP, P2, etc.) as a "staircase" of concepts, depicted in Fig. 1. The lower terms in the staircase are subsets of the higher terms. The components of environmental management systems vary for each item based on the specific requirements of implementing the concepts at the respective steps of the "staircase".

These concepts can also be divided into three levels: global/macro-scale, corporate/firm-wide, and operational. In order to obtain a hierarchical structure of these concepts, however, the staircase model of Hamner [6] was combined with goal, strategy, methods,

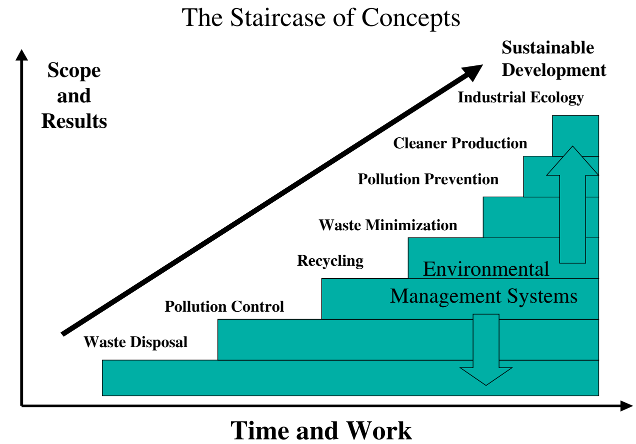

Fig. 1. The staircase of concepts for environmental management systems (after Hamner [6]).

and tasks. This hierarchical structure is illustrated in Fig. 2.

The relationship shown in Fig. 2 provides a mechanism to apply local/operational activities at the global level using a bottom–up structure. This structure positions IE as a delivery tool for SD goals.[1] The SD goals can be operationalized through an IE framework, which would be used for developing relevant CP and P2 strategies at the corporate or organizational level for effective decision-making. Waste minimization and recycling are mainly planning activities at the operational level, which could be integrated into both long- and short-term planning. Pollution control and waste disposal are part of production activities at the operational level satisfying the strategies and policies of CP and P2 using the IE Framework at a top level.

IE and CP/P2 concepts are emphasized in this paper for implementation in the mining industry. These operational level concepts are quite commonly used, incorporated into a strategic mine plan, short-term production plan of a mining operation, and operational plan of a mineral processing plant. However, key to the overall success of meeting the SD goals as corporate objectives is performing the operational activities identified in CP or P2 strategies and policies.

4. Implementing industrial ecology in the mining and mineral industry

The concept of "industrial metabolism", developed by Robert Ayers [12] in 1989, is a system by which industry uses materials and energy flow and then dissipates spent and unused products as wastes. Using a methodical approach of recording material and energy flow in an industrial system and by performing mass

[1] This is in line with the idea that IE is the science of SD.

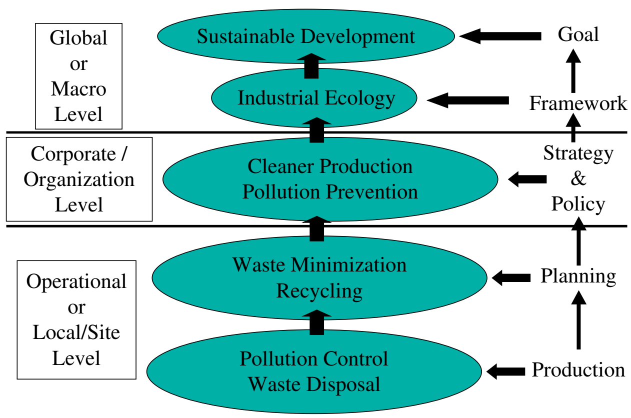

Fig. 2. A hierarchical structure showing the relationships of EMP concepts at various levels.

balances, one could identify inefficient processes or products and their negative impacts on an ecosystem. Frosch and Gallopoulos [13] introduced the concept of ''industrial ecosystem'', from which the term ''industrial ecology'' evolved. A detailed review of the development and implementation of industrial ecology is beyond the scope of this paper but in general, the field includes studies of the following:

- Materials flows;
- Life cycle analyses of products; including recycling, remanufacturing, etc.;
- Energy use and efficiency, renewable energy;
- Green house gas emissions;
- Grand cycles of nitrogen, carbon, etc.; and
- Earth systems engineering.

Research projects are ongoing in many of these topical areas in a variety of fields. Mining and mineral processing-related research is also ongoing, especially in the areas of materials flows [14] and life cycle assessments [15].

The definitions introduced in the earlier section emphasize that an industrial system cannot be seen in isolation from its surroundings, which is the most important reason for implementing an IE framework at a mining or mineral processing operation. Mining and mineral processing operations are multidisciplinary and demand complex interactions between natural and industrial systems.

There are three factors of IE that must be optimized [8]: resources, energy, and capital. A major IE objective is to optimize these components. The mining and minerals industry is a resource-based industry, and demands extensive use of energy and capital. Therefore, this industry is a prime candidate for IE implementation. This requires implementation of a performance management system, most commonly referred to as ''environmental performance'', which has the ability to show trends, scales, and the relations of materials consumed, emitted, dissipated, and discarded [16]. Developing a set of relevant indicators to measure sustainable development would be the first step for establishing a performance measurement system [5,17].

Fig. 3 shows the proposed IE framework that could be implemented for developing CP and P2 strategies and policies at the corporate/organization level for guidance at the operational level. This framework would also facilitate good governance through integrated decision-making.

5. Cleaner production (CP) and pollution prevention (P2)

Cleaner production (CP) and pollution prevention (P2) are used here interchangeably. CP, a subset of IE (as shown in Fig. 3), promotes growth with minimal environmental impact under present technological limits. CP strategies should be developed at the corporate/organizational level, which would help develop action plans for its subsets: waste minimization, recycling, pollution control, and waste disposal at the production level. CP is a dynamic process, which strives for continuous improvement, incorporating state-of-the-art engineering design and other technical and financial capabilities. The UNEP international declaration on CP [18] has over 1000 signatories, including national governments, companies, business associations, NGOs, academic institutes and societies, and international agencies.

CP strategies could be starting points for introducing corporate or organizational (e.g., government) level governance schemes for mining and mineral processing operations striving to achieve pollution prevention and

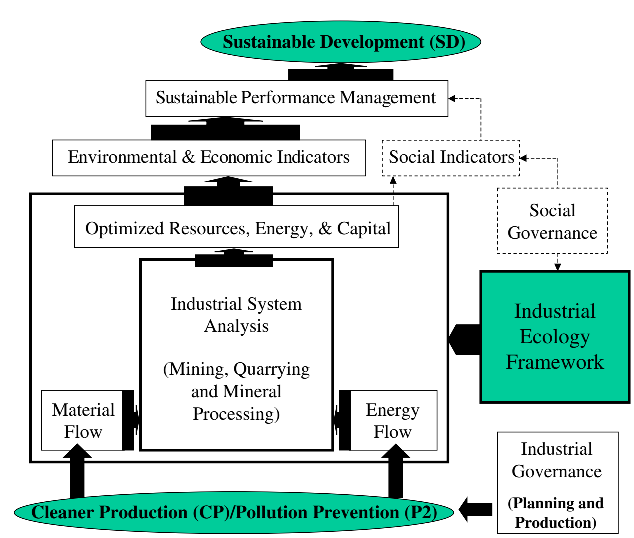

Fig. 3. Industrial ecology framework implementation in the mining and minerals industry.

waste minimization goals. Hilson and Murck [19] presented a review of progress toward pollution prevention and waste minimization in the North American gold mining industry. This progress was measured at the operational or site level with respect to cyanide treatment and acid drainage. In terms of documentation, a good example of CP implementation for mining in mineral industry is the "Best Practice Environmental Management for Mining Series", published by Environment Australia [20]. The key management elements for a CP program identified in this document are as follows:

- Corporate commitment;
- Integrating environmental management systems with general corporate management systems;
- Selecting a core team with detailed knowledge covering all the business units, which can in turn involve the entire workforce;
- Environmental cost accounting – to identify and monitor total environmental costs in parallel with other costs facing the operation; and
- Structured and proven methodology for implementing cleaner production, including assessment of environmental benefits and cost savings as well as communicating these assessments.

Embracing the CP strategy, as shown in Figs. 2 and 3, is a key to operationalizing the IE concept in the mining and mineral industry. Fig. 4 demonstrates the operational level activities' linkages to the corporate strategy of CP for mining operations and mineral processing activities.

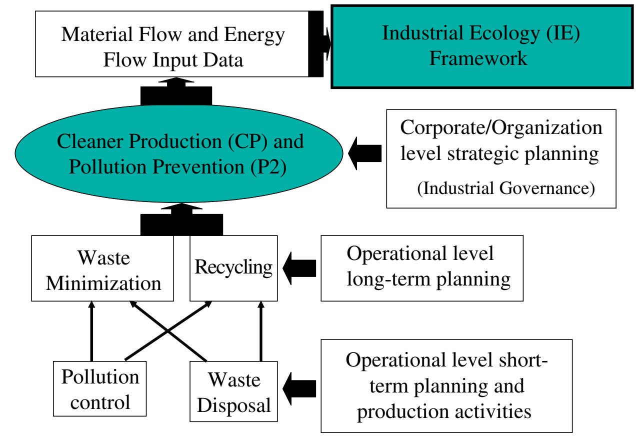

Fig. 4. Cleaner production (CP) at the corporate and operational levels.

6. Conclusions

This paper has introduced the IE concept in the mining and mineral processing industry as a potential framework for enhancing its contribution to sustainable development. IE has been called the science of SD and the framework proposed fits this notion. CP and P2 are important components of an overall IE strategy and must be effectively deployed at the operational level. While many components of CP, P2 and IE are presently employed in the industry, there is not a consistent process by which their implementation on a broad industry scale has been promoted. Implementing the IE framework as a top-level corporate/organizational strategy could contribute to the broader implementation of CP and P2.

Ongoing research and active implementation of IE principles and approaches in the mining and minerals industries should be pursued. Such a systems approach, where the interactions between industrial processes as well as industrial and ecological processes are optimized – or at the very least considered on an integrated basis – must aim to identify better approaches and greater contributions to sustainable development.

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