Clean Techn Environ Policy (2009) 11:307–322
DOI 10.1007/s10098-008-0187-y

ORIGINAL PAPER

Collaborative profitable pollution prevention: an approach for the sustainable development of complex industrial zones under uncertain information

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Received: 13 February 2008 / Accepted: 25 September 2008 / Published online: 28 October 2008

Abstract Pollution prevention (P2) has played an integral role in the development and implementation of technologies designed to prevent the amount of waste generated at a facility. The idea of P2 was later expanded by determining minimum system material and energy requirements, thus reducing the amount of raw materials and economic investment needed. This principle, which considers environmental and economic elements, was termed profitable P2 (P3). This paper, which further expands on the principles of P2 and P3, focuses on utilizing the idea of collaborative P3 (CP3) to aid in decision-making toward sustainable development. CP3 includes a system modeling and analysis methodology, which provides industrial decision-makers with the ability to assess the industrial units' state of sustainability, evaluate future production options, and aid in the selection of the production plan with the best possibility of working toward the sustainable development of not only a single unit, but also of the overall industrial zone. To demonstrate the efficacy of the methodology, a comprehensive study on sustainable development of an auto-manufacturing focused industrial zone is illustrated.

Keywords Collaboration · Profitable pollution prevention · Analysis · Uncertainty

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Introduction

Industries today are facing multiple challenges from several facets of their business, particularly due to increased pressures that can be attributed to industrial globalization, energy depletion, raw material availability, stricter environmental regulations, social responsibility compliance, and the need for new technological advances. It is imperative that industries adopt practices that will aid them to not simply survive, but prosper, in this era consisting of each of these future challenges. It is clear that industries must actively seek approaches toward the goal of sustainable development.

Sustainable development refers to a continuous process of improvements that must be followed in order to achieve a state of sustainability. Practically, sustainable development looks to simultaneously achieve the triple bottom lines of sustainability, a need to: (1) create more value, wealth, and profits in the economically viable dimension, (2) provide cleaner products with less raw resource consumption and waste generation in the environmentally compatible dimension, and (3) have more socially benign products, services, and impacts in socially responsible dimension (Odum 1996).

An industrial zone is defined as a geographic area comprised of a network of industrial sectors, each composed of a number of entities. Such a zone is highly integrated and complex, and contains numerous uncertainties due to each industry's extreme dependencies on its suppliers and customers throughout the product supply chain. In order to work towards the sustainable development of an industrial zone, the zone and the entities that comprise it must focus on a continuous process of environmental, economic, and social advancements.

The realm of industrial sustainability is vast, with many possibilities and definitions. This paper, however, analyzes the triple bottom lines of industrial sustainability in the following manner. Environmentally speaking, there is a need for minimizing the amount of waste generated from a facility. Pollution prevention (P2) serves as a plan of action in order to achieve this objective and the extent of waste generation is a measure of the effectiveness of the P2 technology. The economic interest for each entity within an industrial zone is to maintain profitability, which can be achieved through the reduction of operating expenses. The effectiveness of the economic modifications can be measured by way of a percentage of improvement from a previous year, etc. Finally, from a social point of view, many perspectives have been declared at attempting to properly define the social aspect of sustainability. It has been commented that although the societal aspects of sustainability may appear as being difficult to quantify in terms of metrics, in the technology manner of speaking, the social outlook should be thought of as socially responsible technologies, i.e., technologies that provide quantifiable benefits for all involved (Sikdar 2003). Extending this definition from an individual plant to the scope of an industrial zone, this work identifies the social need for a synergistic approach among the member entities of the zone. A suitable plan of action in order to satisfy this need is the establishment of collaboration and direct relationships among all entities involved in the supply chain, i.e., the corporations, employees, suppliers, investors, communities, customers, etc. The measurement of the level of improvement from a previous scenario could serve as a measure of the effectiveness of the collaborative efforts.

In order for economic, environmental, and social sustainability improvements to be successfully implemented within an industrial zone, the industrial decision makers must possess system-wide analysis abilities. The analysis of the sustainable development of an industrial zone involves decisions at the local, regional, or national levels, which are complex and involves handling of ill-defined parameters with a high degree of uncertainty due to the imperfect understanding of the underlying issues (Andriantiatsaholiniaina et al. 2004). Thus, in attempting to improve the sustainable development of an industrial zone through educated and effective investigations, the data uncertainties and information complexities cannot be ignored and must be addressed. Many methods regarding how to handle these various types of uncertainties currently exist, which include techniques that are fuzzy logic, artificial intelligence, or statistical based (Ayyub and Gupta 1997; Graham and Jones 1988; Zimmermann 1991). Despite the existence of numerous types of inherent uncertainties and uncertainty-handling methods, this work focuses strictly on the uncertainties in future zone planning and a scenario based approach that can be used to evaluate the sustainable development of an industrial zone under these uncertainties. Examples of uncertainties that arise in future zone planning include potential modifications to environmental policies, uncertain market demand, uncertain supply chain structures, etc.

This paper will further discuss how collaboration in conjunction with the principles of P3, i.e., collaborative P3 (CP3), can further aid an industrial zone in moving toward the direction of sustainability. As mentioned earlier, the CP3 development includes a general system modeling and analysis methodology, which provides decision-makers with the ability to assess the effect future industrial zone changes (which are known due to collaboration) will have on the zone's sustainable development. The framework evaluates future production options and aids in determining the production plans with the most positive impact on not only their own sustainability, but also the sustainability of the overall industrial zone.

Collaborative profitable pollution prevention (CP3) for improved sustainable development

In order to improve the analysis capability in studying the sustainable development of an industrial zone, it is necessary to have a methodology for characterizing and managing data uncertainty. In this regard, collaborative profitable pollution prevention (CP3) is derived as an extension from the concepts of P2 and P3 (Lou and Huang 2000). Whereas pollution control refers to post-process based waste treatment technologies, P2 refers to the maximum feasible reduction of all wastes, including wastewater, solid waste, and air emissions generated at production sites (Cushnie 1995). P2 technologies focus on source waste reduction by decreasing the amount of waste generated from a given process. This has resulted in the development and implementation of various technologies, each essentially geared towards the areas of technology change, material substitution, in-plant recovery/reuse, and treatment, many of which require a sizeable capital investment, may be detrimental to product quality, production efficiency, etc., and hence can be hardly adopted by plants. The dotted curve in Fig. 1 represents the environmental and economic impacts of various P2 technologies. As described in Lou and Huang (2000), environmental cleanness is quantified by index I_w, which can range from 0 (completely unacceptable cleanness) to 1 (complete cleanness). As depicted by the dotted curve of Fig. 1, the implementation of low-cost P2 technologies can only result in a limited amount of waste reduction. Additionally, the more complex the P2 strategy selected (i.e., pretreatment, technology change, material substitution, etc.), the higher the level of environmental cleanness can

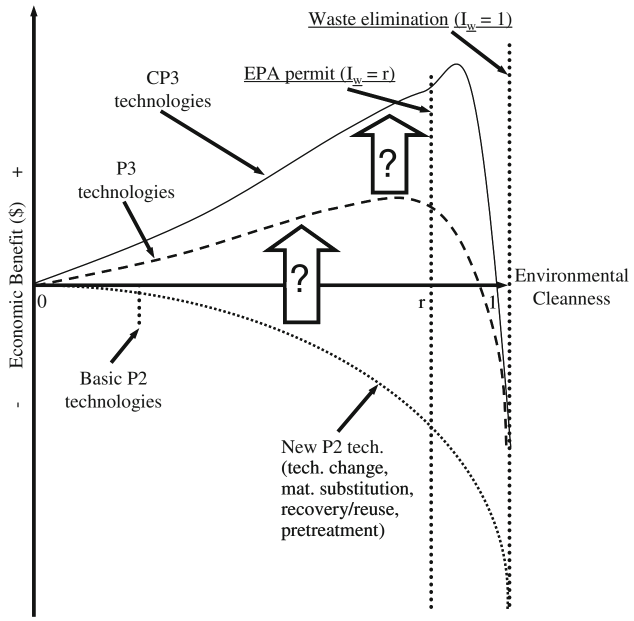


Fig. 1 Economic impact of P2, P3, and CP3 technologies

be achieved (and hence better compliance with EPA regulations), however at a significant capital investment costs to the manufacturer and consequently negative environmental benefit (Lou and Huang 2000).

In order for P2 to gain greater industrial approval, it needs to demonstrate significant improvements to the economic bottom line of the entity implementing the technologies. As such, Lou and Huang extended the P2 theory to develop the next generation of P2 technologies that, in addition to reducing a process' environmental risk, also made profits for plants (Lou and Huang 2000). This concept, which aims to block the channels of waste generation, incorporates both environmental and economic benefits and has become known as profitable P2, or simply P3. P3 technologies are more proactive in nature compared to P2, as they apply a systems view to focus on minimizing the amount of materials and energy needed to supply an operation, thereby also minimizing the amount of "end-of-process" and "end-of-plant" waste generation, and at the same time, ensuring plant profitability through minimizing material and energy consumption and improving productivity and product quality. Due to the fact that this type of P2 strategy requires little to no capital investment and decreases operating costs by significant margins, the economic benefit of P3 technologies are positive, as displayed by the dashed curve in Fig. 1. A number of P3 projects have been successfully applied and implemented in the electroplating industry, demonstrating the value of P3 and its ability for translation into practice (e.g., Huang 2002, 2007).

It is clear from the definition above that P3 technologies encompass and address two of the triple bottom lines associated with the study of sustainability as defined by this work, i.e., the economic and environmental aspects. However, it fails to consider the dimension of social sustainability, which for this work has been defined as the need for synergistic efforts amongst the members of an entire product supply chain (i.e., suppliers, the local and global communities, customers, etc.). In order to achieve this level of synergy, there is an unmistakable need for collaboration and a direct relationship among all involved in the supply chain (i.e., the corporations, employees, suppliers, investors, communities, customers, etc.).

The idea of collaboration (social) can be thought of as an action that must be taken, in conjunction with the action of waste prevention that is achieved through the implementation of various P2 technologies (environmental), in order to result in even higher positive economic benefits for the entities or zones implementing the techniques (i.e., profitable). The combination of these three elements is the basis of the idea of CP3, which is further discussed below.

Equation 1 is an extension of a P3 principle introduced by Lou and Huang (2000), which maintains that P3 techniques result in the joint realization of increased profits (production) and waste reduction at the process level. Equation 2 extends this P3 principle to the industrial zone level, which includes multiple plants and collaboration and coordination amongst the plants.

$$\begin{aligned}\text{P3} &= \text{Regional profit} \uparrow + \text{Regional waste} \downarrow \\ &= \sum^{\#\text{processes}} \left(\text{Profit} \uparrow + \frac{1}{\text{Waste}} \uparrow \right) \qquad (1)\end{aligned}$$

$$\text{CP3} = \sum^{\#\text{plants}} \left(\text{Profit} \uparrow + \frac{1}{\text{Waste}} \uparrow \right)_{\text{Collaboration}} \qquad (2)$$

Furthermore, in order to achieve a successful level of collaboration within an industrial zone, a systematic collaboration strategy must be created and implemented, which includes: (1) generate a system description through modeling, (2) develop a model based analysis on profit and waste, (3) identify key issue(s) effecting economic and environmental sustainability, (4) develop a collaboration strategy, (5) assess the benefits of the developed collaboration strategy, and (6) implement collaboration strategy if economically, environmentally, and socially acceptable.

Based on the above discussion, the level of economic benefit as a function of environmental cleanness by taking a CP3 approach can be created, as displayed by the solid curve of Fig. 1. Figure 2 illustrates the 3-D impact of collaboration of economic and environmental progress. It is

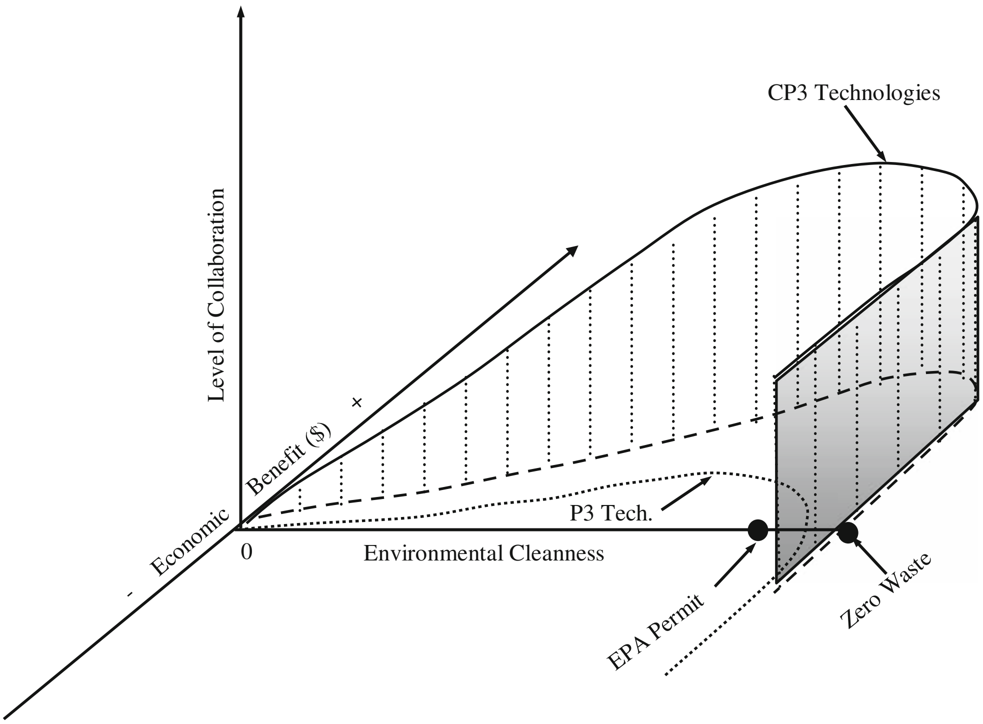


Fig. 2 Impact of collaboration on economic and environmental progress

clear from Figs. 1 and 2 that collaboration and synergy within a supply chain can result in improved effectiveness over the implementation of P3 techniques alone.

The remainder of this paper will discuss an approach for generating a general systems-based industrial zone description through modeling, along with a discussion of the usefulness of the models in assessing and evaluating the level of improvement in working toward the sustainable development of an industrial zone.

General modeling

The analysis for sustainable development must be conducted from a systems point of view. More specifically, it should look to simultaneously improve the material and energy efficiencies, product quality and variety, and productivity within an industrial zone, thus pursuing the long-term development of a given industry. At this stage, this work focuses solely on material issues within an industrial zone, although the possibility for the extension into characterizing energy issues also exists. An industrial zone refers to a geographic zone comprised of a network of industrial sectors, each composed of a number of entities (Fig. 3). It is quite clear from the figure that the complexities associated with the study of the sustainability of an industrial zone are vast. As discussed earlier, an industrial zone is usually highly integrated and each industry within the zone is extremely dependent on its suppliers and customers throughout the product supply chain.

This section discusses an approach for generating a general systems-based industrial zone description through modeling, while the collaboration analysis strategy, which is required in order to provide the user with meaningful recommendations based on a given system, is discussed later.

System modeling

Although numerous methods are available to model a system, including the modified ecological input-output analysis method (Piluso et al. 2008; Piluso and Huang 2007), the models introduced in this work begin with a plant-based model and extended to the development of a zone level model. Due to the fact that the study of a sustainable development problem focuses on the time intervals of years or decades, a conventional continuous equation lacks meaning, as sustainability is not an issue on the scale of seconds, minutes, hours or even days. As such, the equations to model the flow through an entity within an industrial zone in this work are given in discrete form, thus allowing for evaluation in time-step intervals.

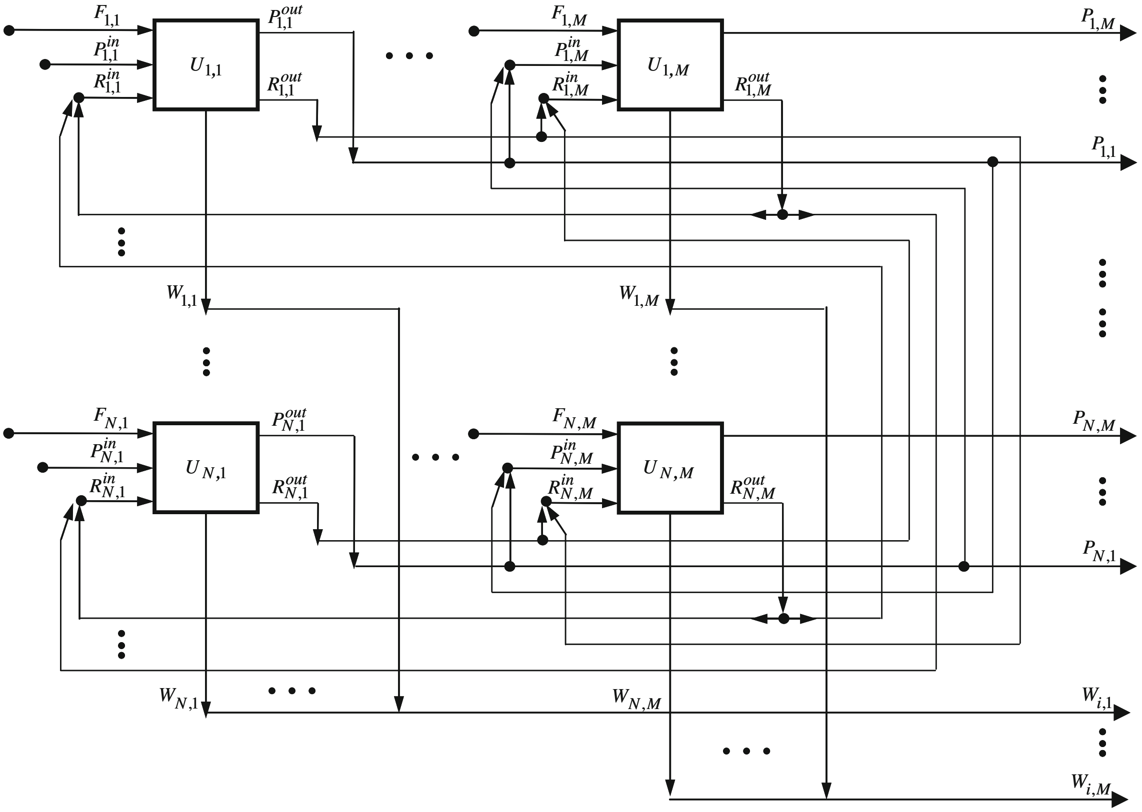


Fig. 3 General composition and complexity of an industrial park

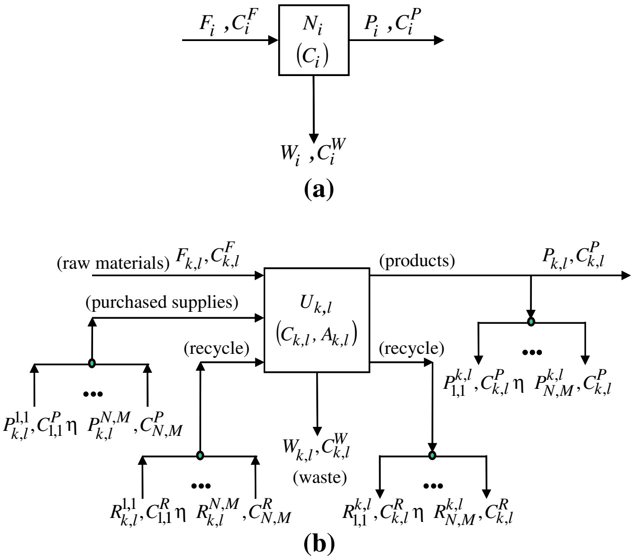


Fig. 4 **a** Plant-based mass flow model: a simple flow example, and **b** a flow system involving recycles and multiple supplies

Since the following discussion of the plant, industry, and zone level models does not include the derivation of the continuous form of the equations, a simple example is now given in order to aid the reader in understanding how the discrete equations are derived. Figure 4a depicts the structure of a manufacturing entity (N_i) that requires one input flow stream (F_i) with composition C_i^F in order to produce a product (P_i) and waste (W_i) stream. It is also assumed that the concentrations of the product and waste streams, C_i^P and C_i^W, respectively, are uniform to the concentration within unit N_i (i.e., C_i) and that the total mass flow into unit N_i is given as $\rho_i V_i$. Based on this information, the continuous mass balance equation is given below.

$$\frac{\mathrm{d}C_i}{\mathrm{d}t} = -\frac{[P_i + W_i]}{\rho_i V_i} C_i + \frac{F_i}{\rho_i V_i} C_i^F \tag{3}$$

which is discretized as:

$$C_i(n+1) = \left(1 - \frac{[P_i + W_i]}{\rho_i V_i}\Delta t\right) C_i(n) + \frac{F_i}{\rho_i V_i} \Delta t C_i^F(n) \tag{4}$$

The discrete form in Eq. 4 is most useful for application to a sustainable development problem, which allows for the calculation of a future time interval, e.g., 5 or 10 years into the future.

Plant (unit) based model

The basis of the model development for this work is that of a material balance over an entity with three types of inputs (raw material, product, and recycle from other entities) and three types of outputs (product, recycle, and waste). Additionally, it is assumed that the compositions of an outlet stream are uniform to that within the unit. In order to model the flows within a given industrial network, a model must be developed beginning from the unit or plant based level (see Fig. 4b). The discrete form of an individual plant ($U_{k,l}$) is given below.

$$C_{k,l}(n+1) = \left(1 - \alpha_{k,l}\,\Delta t\right) C_{k,l}(n) + \sum_{i=1}^{N}\sum_{j=1}^{M} \beta_{k,l}^{i,j} C_{i,j}(n)\,\Delta t + \gamma_{k,l}\,\Delta t\, C_{k,l}^{F}(n) \tag{5}$$

where

$$\alpha_{k,l} = \frac{1}{A_{k,l}}\left[\sum_{i=1}^{N}\sum_{j=1}^{M}\left(E_{i,j}^{P_{k,l}} P_{i,j}^{k,l} + E_{i,j}^{R_{k,l}} R_{i,j}^{k,l}\right) + P_{k,l} + W_{k,l}\right] \tag{6}$$

$$\beta_{k,l}^{i,j} = \frac{1}{A_{k,l}}\left(E_{k,l}^{P_{i,j}} P_{k,l}^{i,j} + E_{k,l}^{R_{i,j}} R_{k,l}^{i,j}\right) \tag{7}$$

$$\gamma_{k,l} = \frac{F_{k,l}}{A_{k,l}} \tag{8}$$

where

M	the total number of industries within zone
N	the total number of supply chains within zone
$A_{k,l}$	the total mass into unit $N_{k,l}$
$C_{k,l}$	the component composition within unit $N_{k,l}$

It should also be noted that for each derived equation, whether at the plant, industrial sector, or zone level, the base letter refers to the type of flow being described, i.e., either raw material (F), product (P), recycle (R), or waste (W); for instance, $W_{k,l}$ represents the waste stream from plant k,l. Additionally, the superscripts refer to the plant generating the flow and the subscripts indicates the plant that is receiving the flow, i.e., $P_{k,l}^{i,j}$ represents the product flow rate from unit i,j to unit k,l.

The output from entity $U_{k,l}$, described by the $\alpha_{k,l}$ term, contains four possibilities, product and recycle flows to another entity, $U_{i,j}$, within the zone, $P_{i,j}^{k,l}$ and $R_{i,j}^{k,l}$, respectively, products sold outside of the zone, $P_{k,l}$, or waste generation, $W_{k,l}$. Similarly, the product and recycle inputs to entity $U_{k,l}$ from other units located within the zone, $P_{k,l}^{i,j}$ and $R_{k,l}^{i,j}$, are described by the $\beta_{k,l}^{i,j}$ term (Eq. 7) and inputs from the environment or outside of the zone of study are given by $\gamma_{k,l}$ of Eq. 8.

Additionally, Eqs. 6 and 7 contain binary variables, which are designed to restrict or control the flow structure within an industrial zone; they are defined as:

$$E_{i,j}^{P_{k,l}} = \begin{cases} 0 & \text{if} \quad j \le l \\ 0 & \text{if} \quad \text{flow connection does not exist} \\ 1 & \text{otherwise} \end{cases} \tag{9}$$

$$E_{k,l}^{P_{i,j}} = \begin{cases} 0 & \text{if} \quad j \ge l \\ 0 & \text{if} \quad \text{flow connection does not exist} \\ 1 & \text{otherwise} \end{cases} \tag{10}$$

$$E_{i,j}^{R_{k,l}},\ E_{k,l}^{R_{i,j}} = \begin{cases} 0 & \text{if} \quad j = l \\ 0 & \text{if} \quad \text{flow connection does not exist} \\ 1 & \text{otherwise} \end{cases} \tag{11}$$

Equations 9 and 10 place restrictions on the product from a given entity from being sold back into the supply chain or within the same industry, and Eq. 11 places a restriction on the recycle streams being sold within the same industry. Additionally, although a flow could exist after these flow restrictions are imposed, other factors may exist for the flow not being connected, i.e., which suppliers are selected, etc. Thus, Eqs. 9 through 11 also provide the opportunity to set a flow to zero if a flow connection does not exist.

The binary coefficient terms $E_{i,j}^{P_{k,l}}$, $E_{k,l}^{P_{i,j}}$, $E_{i,j}^{R_{k,l}}$, and $E_{k,l}^{R_{i,j}}$ can also be viewed as decision-making variables, where the elements $j \le l$, $j \ge l$, and $j = l$ of Eqs. 9 through 11 are constraints that are placed on the system. Additionally, the binary value conditions of Eqs. 9–11 are constraints based on the flow connections of the existing network. This setup could be quite useful in future work, which could extend the introduced CP3 work to include the optimization of flows within an industrial zone.

It is also important to note that each of the plant, industry, and zone models are static in nature over a given time interval Δt, the sustainable behavior does not change. The methodology, however, allows evaluation at multiple time intervals, representing sustainability assessment a number of years into the future.

Industry (subsystem) based model

Given the model structure for a single unit or plant, the model can be extended to quantify the flow dynamics throughout an industry, which is composed of multiple units or plants. The discrete expression for the industry, l as depicted by a column in Fig. 3, can be described as follow:

$$\boldsymbol{C}_l(n+1) = (\boldsymbol{I} - \alpha_l \Delta t)\boldsymbol{C}_l(n) + \beta_l \Delta t \boldsymbol{C}(n) + \gamma_l \Delta t \boldsymbol{C}_l^{F}(n); \quad l = 1, \ldots M \tag{12}$$

where

$$\boldsymbol{C}_{\mathbf{l}}(n) = \left(C_{1,l}(n) \cdots C_{N,l}(n)\right)^T \tag{13}$$

$$\begin{aligned}\boldsymbol{C}(n) = \big(&C_{1,1}(n) \cdots C_{N,1}(n) C_{1,2}(n) \cdots C_{N,2}(n) \\ &\cdots C_{1,M}(n) \cdots C_{N,M}(n)\big)^T\end{aligned} \tag{14}$$

$$\boldsymbol{C}_{\boldsymbol{l}}^{\boldsymbol{F}}(n) = \left(C_{1,l}^F(n) \cdots C_{N,l}^F(n)\right)^T \tag{15}$$

$$\boldsymbol{\alpha}_{\mathbf{l}} = \operatorname{diag}\left(\alpha_{1,l} \cdots \alpha_{N,l}\right) \tag{16}$$

$$\boldsymbol{\beta}_{\mathbf{l}} = \begin{pmatrix} \beta_{1,l}^{1,1} \cdots \beta_{1,l}^{N,1} & \beta_{1,l}^{1,2} \cdots \beta_{1,l}^{N,2} & \cdots & \beta_{1,l}^{1,M} \cdots \beta_{1,l}^{N,M} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{k,l}^{1,1} \cdots \beta_{k,l}^{N,1} & \beta_{k,l}^{1,2} \cdots \beta_{k,l}^{N,2} & \cdots & \beta_{k,l}^{1,M} \cdots \beta_{k,l}^{N,M} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{N,l}^{1,1} \cdots \beta_{N,l}^{N,1} & \beta_{N,l}^{1,2} \cdots \beta_{N,l}^{N,2} & \cdots & \beta_{N,l}^{1,M} \cdots \beta_{N,l}^{N,M} \end{pmatrix} \tag{17}$$

$$\boldsymbol{\gamma}_{\mathbf{l}} = \operatorname{diag}\left(\gamma_{1,l}, \ldots \gamma_{N,l}\right) \tag{18}$$

Zone (system) based model

Finally, the subsystem model can be extended to quantify the flow dynamics throughout an industrial zone, which is composed of multiple industries. The discrete expression for an industrial zone, as shown in Fig. 3, can be described as follows:

$$C(n+1) = (I - (\alpha + \beta)\Delta t)C(n) + \gamma \Delta t C^F(n) \tag{19}$$

where

$$C(n) = \left(\boldsymbol{C}_{\boldsymbol{1}}(n) \cdots C_M(n)\right)^T \tag{20}$$

$$C^F(n) = \left(\boldsymbol{C}_{\boldsymbol{1}}^F(n) \ \cdots \ C_M^F(n)\right)^T \tag{21}$$

$$\boldsymbol{\alpha} = \operatorname{diag}(\boldsymbol{\alpha}_{\mathbf{1}} \ \cdots \ \boldsymbol{\alpha}_{\mathbf{M}}) \tag{22}$$

$$\boldsymbol{\beta} = (\boldsymbol{\beta}_{\boldsymbol{1}} \cdots \boldsymbol{\beta}_{\boldsymbol{M}})^T \tag{23}$$

$$\boldsymbol{\gamma} = \operatorname{diag}(\boldsymbol{\gamma}_{\boldsymbol{1}} \ \cdots \ \boldsymbol{\gamma}_{\boldsymbol{M}}) \tag{24}$$

Sustainability analysis procedure under uncertainty

As mentioned earlier, this work discusses a modeling framework along with an analysis procedure, which is designed to address the basic issues of uncertainty in the study of the sustainability of a complex industrial zone. An analysis procedure should provide the user with meaningful recommendations based on a given system. The combination of the modeling and analysis procedures provides industrial forecasters with the ability to utilize the system-based information gained from the analysis to assess the effect of future industrial zone changes on the zone's sustainable development over time. This is accomplished by way of evaluating future production options to determine the production paths with the most positive impact on not only their own sustainability, but also the sustainability of the overall industrial zone.

Inherent uncertainty in industrial sustainability data

Sustainable development is an ongoing process. It is natural that complex systems, such as industrial zones, are filled with uncertainty and no amount of precaution will eliminate all risks (Newman 2005). Since an industrial sustainability problem is typically large scale, a proper analysis requires a variety of data and information. Unfortunately, the available information is frequently uncertain, incomplete, and imprecise, thus making an effective sustainability-focused analysis extremely difficult.

Uncertainties may arise from numerous sources, including directly from the data selected, by way of incomplete or imprecise available data, model parameter uncertainty, where assorted process inputs will affect the model coefficients, thus leading to uncertainties with regard to future zone sustainable development status, and/or simple lack of understanding of the fundamental issues in addressing the problem of the sustainable development. The specific inherent uncertainties in the data required during the study of the sustainable development of an industrial zone analysis arise from the incomplete and complex nature of the structure of the industrial zone or zone. For example, the multifaceted makeup of the inter-entity dynamics, dependencies, and interrelationships, the uncertain prospect of forthcoming environmental policies (both short and long term), and the indistinct interrelationship between the triple bottom lines of industrial sustainability (i.e., how the environmental, economic, and societal components of the zone effect each other) are all uncertain. Furthermore, the specific data regarding material or energy consumption, product, waste, or by-product generation, amount of recycle, and profitability of an individual plant, industry, or zone are often incomplete. Additionally, it is only natural that as the size and scope of a problem increase, the amount of available reliable data decreases and the risk of data uncertainty increases, simply due to the incomplete awareness of the causal problem.

In order for an effective industrial sustainability analysis to be made, the data uncertainties must be properly handled. This work looks to manage uncertainties due to future zone planning decisions. For instance, the unclear future of supply chain issues, such as supplier availability and selection and the modification of environmental regulations, etc. By way of the evaluation of multiple scenarios, where multiple planning options can be assessed, using the above described modeling techniques, it can be ascertained how various inputs effect the sustainable development of the industrial zone of interest. This procedure will be further clarified in the case studies to follow.

Sustainability analysis

The industrial sustainability modeling and analysis framework is given in Fig. 5. The analysis begins with the user providing any available system information, which could include data such as individual plant data (production, raw material consumption, waste generation and compositions, future planning schedules, etc.), zone development data, environmental regulation or policy information, cost data, etc. Next, the CP3 system modeling approach is implemented to calculate individual plant, industrial, and/or zone production (measure of economic performance) and waste generation (measure of environmental performance) data, over time. Since sustainable development refers to a continuous process of improvements that must be followed in order to achieve a state of sustainability, the ability to model over a given time span is extremely important. As such, the modeling procedure allows us to model the zone at several time intervals, thus providing a time-dependent model of the industrial zone's sustainable development. Subsequently, the data obtained from Step 2 of the modeling and analysis framework is used to analyze the zone's sustainable development from the economic, environmental, and social (by way of amount of collaboration performed) dimensions.

As mentioned above, economically speaking, this analysis consists of quantifying the plant, industry, and zone's annual production of the species of interest. Production is used as the measure of economic sustainability due to its direct relationship to profits. Similarly, from an environmental standpoint, the amount of waste generated from each plant, industry, or the zone as a whole is calculated. The social sustainability metric, which is more difficult to quantify, is assessed based on the extent of collaboration performed within the zone.

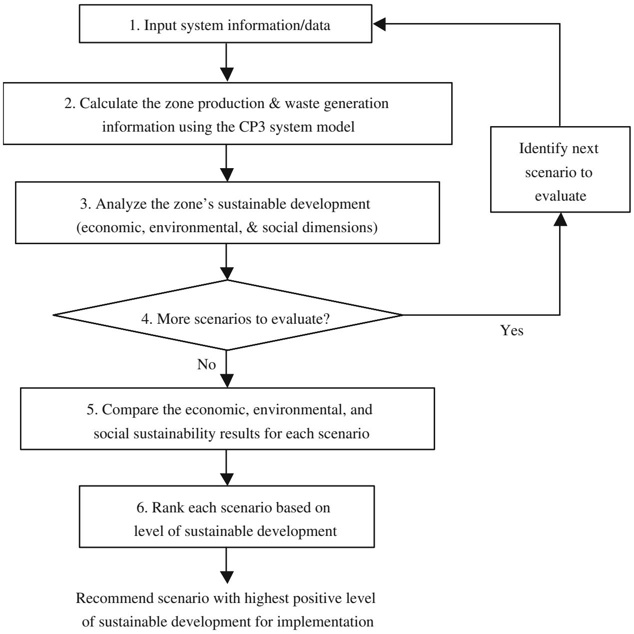


Fig. 5 Industrial sustainability modeling and analysis framework

In the case where more scenarios are to be evaluated, Steps 2 and 3 are repeated until all scenarios have been evaluated. Subsequently, economic, environmental, and social comparisons can be made between the various alternative production strategies and each scenario can be ranked in order of level of sustainable development achieved. Finally, a recommendation for implementation can be made to the industrial planners based on the scenario rankings provided in Step 6. The application and usefulness of the modeling and analysis framework will be further elucidated in the following case studies section.

Case studies

A series of case studies are provided below, which will look to implement the above sustainability modeling and analysis methodology to study the sustainable development issues of a complex auto-manufacturing focused industrial zone, where the available information is uncertain.

Industrial zone description

Figure 6 displays the flow structures and complexities of an industrial zone of interest, which simulates the flow of copper throughout an industrial zone. The case study is composed of three manufacturing industries, the chemical supply industry (represented by entities 1, 2, and 3), the surface finishing industry (represented by entities 4, 5, and 6), and the end-manufacturer, in this case, the automotive industry (represented by entities 7, 8, and 9). The chemical supply entities each have a raw material inlet stream of copper from the environment and the automotive manufacturers each generate a final product for consumer use. Additionally, each of the nine entities generates a copper-containing waste stream, which is discarded to the environment.

Furthermore, all first tier suppliers, i.e., the chemical supply shops, only supply the second tier plating shops, not the automotive industry directly. Additionally, the plating industry directly supplies the automotive industry.

The information provided to the user through the use of the CP3 modeling technique includes plant and zone based production and waste generation information. From the standpoint of the study of the triple bottom lines of industrial sustainability, the environmental analysis can be

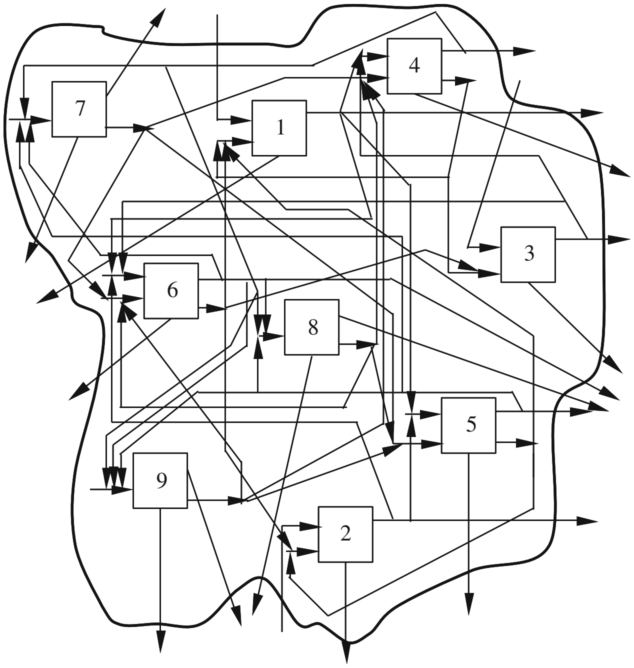


Fig. 6 Automotive centered industrial zone, base case and Case I

evaluated directly from the amount of copper-containing waste generated, both at the plant and zone levels. The economically viable dimension, however, cannot be directly assessed in terms of rate of copper based material production, as this measure does not take into account the capital or operating costs involved in maintaining operation, fluctuations in raw material and product selling prices, etc. As such, the economic sustainability evaluations performed in the case studies to follow convert production into gross profit ($/year), which takes into account the above mentioned economic factors. Although the case study evaluations quantify measures of economic and environmental sustainability, social sustainability, which is extremely difficult to quantify from an engineering point of view, will be evaluated qualitatively, as a measure of the level of zone collaboration achieved for a particular case study. In addition, a qualitative assessment associated with the quantitative economic and environmental sustainability assessments will be given to enhance the case study evaluations.

Base case: increased production without technology advancement

The interest of this study is to assess the sustainable development effects that the copper-containing waste and product that is being generated by the entities in the industrial zone over the time span of 10 years on the individual entities and overall zone. The effect may take place when the feed streams change over time, along with the continuously changing production plans. It is assumed that each plant has two possible production plans (Plans A and B) over the next 10 years, and it is uncertain as to which production plan should be selected, which most positively will benefit the sustainable development of the industrial zone. The sustainability analysis is used to determine which plan should be followed in order to improve their own and the zone's sustainability. A discussion of the difference in results from each of the three case studies will be conducted after the introduction of the three case studies is completed.

In the base case, chemical supply plants 1, 2, and 3 each need to analyze two potential paths for increasing their production over the next 10 years (see Fig. 7). The first step of the modeling and analysis framework requires the input of all available system information or data. For this case, the inlet copper flow information is given in Fig. 7. Step 2 of the framework requires the use of the sustainability modeling methodology to determine the production and waste generation for each entity within the industrial zone. Continuing to follow the framework of Fig. 5, the triple bottom lines must be evaluated. The evaluation, as described earlier, consists of quantifying the gross profit (economic) and waste generation (environmental) for each individual plant and the industrial zone. Additionally, social sustainability is qualitatively evaluated as a measure of the level of zone collaboration achieved for a particular case study. It is important to note that the analysis and discussion of this paper will focus on the results from plants 4 and 7 and the overall industrial zone. The base case economic and environmental sustainability results are provided in Fig. 8. Similar data for the remaining zone entities are left out of the discussion for conciseness.

From the economic analysis, Fig. 8a–c, it is clear that gross profit, and hence economic sustainability of plants 4, 7, and the overall zone, is increasing over time for both Plan A and Plan B. However, without any modification to internal recycle capabilities, so too does the amount of copper waste being generated by both the individual plants and the overall zone (Fig. 8d–f). Continuous production in such a manner may result in these operations exceeding the copper waste generation limit in the near future, which is not acceptable. Qualitatively speaking, the environmental sustainability of this scenario is not desirable, whereas economic performance is good, by way of improved gross profits over the 10-year time span. Lastly, since this base case does not consider any zone collaboration or communication, the social aspect of this case is poor.

Since there are still two more scenarios to evaluate, the modeling and analysis framework of Fig. 5 guides us to repeat the above analysis for the remaining scenarios. The

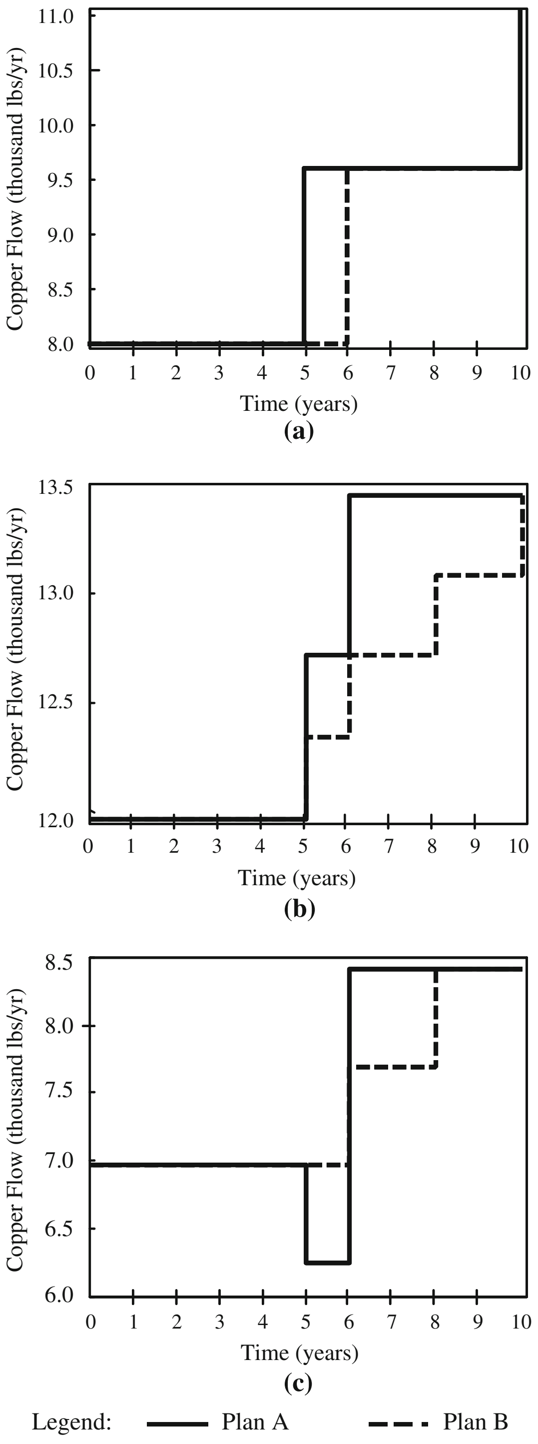


Fig. 7 Copper feed options into industrial zone over time: **a** plant 1, **b** plant 2, and **c** plant 3

next case study, Case I, will analyze the effects of the same raw material increase as above, the difference being that capital investments of varying degrees are made by each plant to improve their internal recycle capabilities, thus improving production and decreasing copper waste generation to the environment.

Case I: increased production with recycle technology advancement

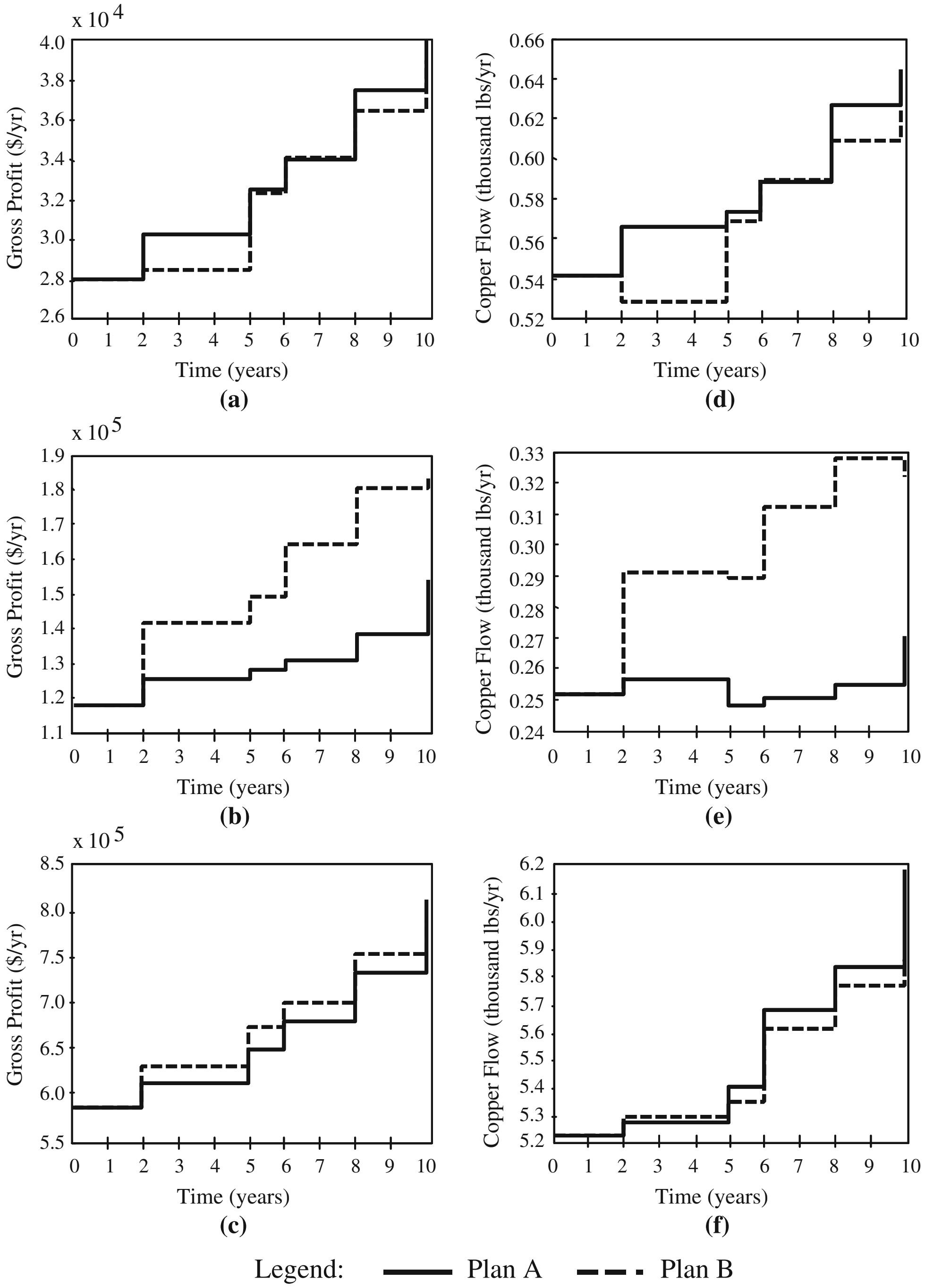
Case I represents the case where chemical supply plants 1, 2, and 3 again each analyze two potential paths for increasing their production over the next 10 years. For the first step in the modeling and analysis framework, it is assumed that the input system is the same as that for the Base Case, therefore given in Fig. 7. Additionally, various plants plan to make capital investments, at assorted time instances in the future, to improve their internal P3 technologies, thus reducing the amount of copper waste being generated over the upcoming 10 years. The sustainability analysis methodology is again implemented to determine the production and waste generation for each entity within the zone.

The second step in the framework shown in Fig. 5, as in the base case, uses the CP3 models to calculate the zone's copper production and waste generation data for each entity within the zone as well as for the overall industrial zone. Once these calculations have been performed, the third step of the framework requires the evaluation of the triple bottom lines. The economic and environmental sustainability results for Case I are provided in Fig. 9 Again, similar data for the remaining zone entities are left out of the discussion for brevity.

From the economic analysis of Fig. 9a–c, it can be seen that as gross profit, and hence economic sustainability, increases over time for both Plan A and Plan B, due to the plant's improved internal recycle capabilities, the amount of copper waste being generated, as expected, steadily decreases over time (Fig. 9d–f), which is beneficial to environmental sustainability. Because of the improved internal waste prevention technologies that have been implemented and the proposed production for all plants within the zone, the zone will generate copper waste under the threshold limit for the foreseeable future. Qualitatively speaking, the environmental sustainability of this scenario can be evaluated as being moderate, still with room for improvement, whereas economic performance is good, by way of improved profits over the 10-year time span of study. Lastly, similar to the base case, since Case I also does not consider any zone collaboration or communication, the social aspect of this case is poor.

One scenario remains to be assessed; therefore, again following the modeling and analysis framework in Fig. 5, the above analysis must be repeated for the remaining scenario. The next case study, Case II, will analyze the effects of the same raw material increase schedule and improved internal recycle capabilities as above, and will additionally, due to zone collaboration and communication, consider modifying the network connections in an attempt

Fig. 8 Base case: economic analysis: **a** plant 4, **b** plant 7, and **c** overall zone. Environmental analysis: **d** plant 4, **e** plant 7, and **f** overall zone



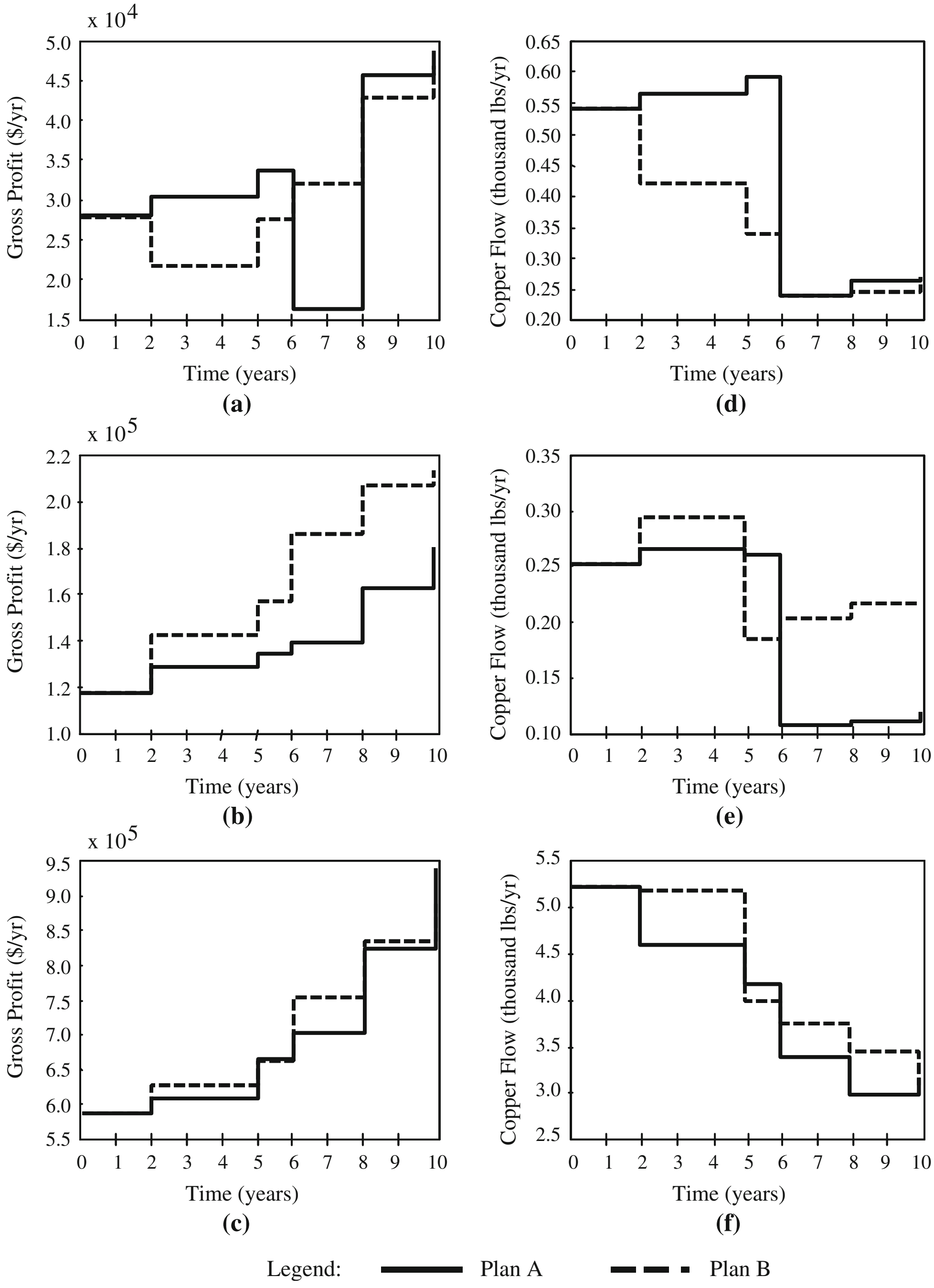
to further improve production and decrease copper waste generation to the environment.

Case II: increased production with recycle technology advancement and modified supply chain connections

Case II corresponds to the one where chemical supply plants 1, 2, and 3 again each analyze two potential paths for increasing their production over the next 10 years. The raw material input into system is again assumed to be the same as that for the Base Case, given in Fig. 7. As in Case I, each plant also makes various capital investments to improve their internal P3 technologies, thus reducing the amount of copper-containing waste being generated over the upcoming 10 years. Additionally, due to improved collaboration and communication among plants within the industrial zone, Case II considers various modifications to the supply chain (i.e., network connections are modified), as displayed in Table 1.

The sustainability analysis methodology is again implemented to determine the production and waste generation for each of the entities within the industrial zone.

Fig. 9 Case I: economic analysis: **a** plant 4, **b** plant 7, and **c** overall zone, environmental analysis: **d** plant 4, **e** plant 7, and **f** overall zone



The next step in the framework, as in the two previous cases, uses the CP3 models to calculate the zone's production and waste generation data. Once these calculations have been performed, the third step of the framework requires the evaluation of the triple bottom lines. The economic and environmental sustainability results for Case II are provided in Fig. 10. Again, similar data for the remaining zone entities are left out of the discussion for brevity.

It can be seen from Fig. 10a–c that as gross profit, and hence economic sustainability, increases over time for both Plan A and Plan B due to the plant's improved internal recycle capabilities and modified network connections, the amount of copper waste being generated decreases over time (Fig. 10d–f), as is expected, which is beneficial to environmental sustainability. Therefore, qualitatively speaking, it can be inferred that the environmental sustainability of this scenario is moderate, again still with room for improvement, conversely, economic performance is good, by way of improved gross profits over time. Due to the fact that this scenario does consider some zone collaboration and communication to aid in individual plant

Table 1 Summary of specific zone modifications made for Case II

Plant	Supply chain modifications
Surface finishing plant #4	Due to unsatisfactory performance by chemical supplier #1, shop #4 decided to replace their supply with that of chemical supplier #2
Surface finishing plant #5	Due to the possibility of chemical supplier #2's upcoming plant closure, shop #5 decided to replace their supply with that of chemical supplier #3
Surface finishing plant #6	Due to quality concerns for product received from chemical supplier #3, shop #6 decided to eliminate supplier #3 as a supplier and buy all copper from suppliers #1 and #2
Automotive OEM #8	Due to cost concerns, OEM #8 decided to eliminate finishing shop #5 as a supplier and now buy all copper plated parts solely from finishing shops #4 and #5
Automotive OEM #9	Due to quality concerns, OEM #9 decided to eliminate finishing shop #4 and buy all their copper plated parts solely from finishing shops #5 and #6

production planning, the social aspect of this case can also be assessed as moderate.

Since all three scenarios have now been evaluated, the assessment can proceed following the remaining steps provided in the modeling and analysis framework in Fig. 5. The following subsection will discuss the final comparison, ranking, and recommendation steps of the framework.

Case comparison, ranking, and recommendations

Case comparison

Once all zone planning scenarios have been evaluated, the remainder of the modeling and analysis framework looks to compare, rank, and finally recommend a scenario for zone implementation. Step 5 of the framework given in Fig. 5 require the comparison of the results (i.e., the triple bottom line analysis) from each scenario. The value of a systems based sustainability analysis is that it allows for the ability to see results that would not be intuitive, due to the complex nature and high interconnection of the entities within the industrial zone.

The previous analysis in Step 3 of the framework in Fig. 5 determined that Case II resulted in the highest level of social sustainability, whereas neither the Base Case nor Case I considered social aspects of sustainability (i.e., collaboration). Since the sustainable development of an industrial zone requires a balance between the triple bottom lines of sustainability, the Base Case and Case I are neglected from further consideration for recommendation and the remainder of the analysis will focus strictly on Case II. This requires a comparison between the remaining two bottom lines of sustainability, economic and environmental, for Plans A and B in Case II for the overall zone, to aid in the ranking of the scenarios providing the highest level of positive sustainable development.

Figure 11 displays both the economic (gross profit) and environmental (waste generation) comparisons of Case II A and B for the overall zone. From an economic standpoint (Fig. 11a), the two scenarios are equal for the first 2 years. After this point, Plans A and B alternate in terms of which case generates the higher gross profit across the zone. Taking the annualized gross profit over the 10-year time span of interest, it is found that Plan A of Case II results in an annualized gross profit of \$660,346/year, whereas Plan B of Case II gains an annualized gross profit of \$657,369/year.

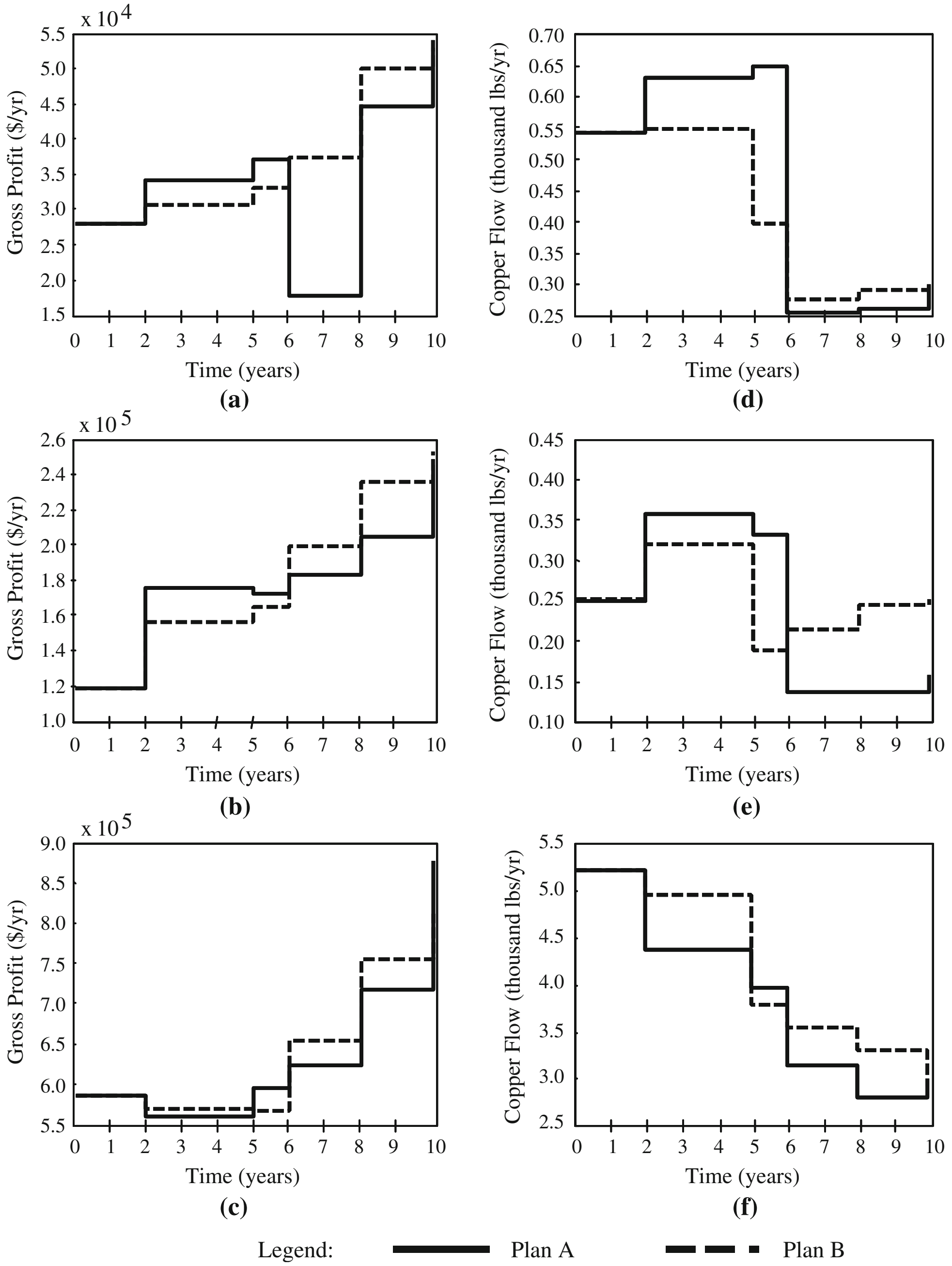
Similarly, environmentally speaking (Fig. 11b), the two scenarios alternate in terms of which case generates the less copper waste across the zone. Taking an average value of waste generation over the 10-year time span of interest, it is found that Plan A of Case II results in the lower generation of waste (3.756×10^3 lbs/year) as compared to Case II B (3.957×10^3 lbs/year).

Case ranking

The sixth step in the modeling and analysis framework is to rank each scenario base on their level of sustainable development. As mentioned above in the discussion of each scenario and the comparison of each case, the quantitative and qualitative economic, environmental, and social sustainability for each case is deduced. Based on these quantitative (for economic and environmental) and qualitative (for social) assessments, the evaluated cases can be ranked in order of best to worst regional sustainable development.

As mentioned earlier, since the sustainable development of an industrial zone requires a balance between the triple bottom lines of sustainability, the Base Case and Case I have already been neglected from consideration for recommendation. The case ranking therefore only focuses on Plans A and B of Case II.

Fig. 10 Case II: economic analysis: **a** plant 4, **b** plant 7, and **c** overall zone, environmental analysis: **d** plant 4, **e** plant 7, and **f** overall zone



The scenario with the highest level of sustainable development is Plan A of Case II, as it resulted in a higher annualized gross profit of $660,346/year and lower average value of copper waste generation (3.756×10^3 lbs/year) over the 10-year time span of interest. Additionally, Plan A of Case II was evaluated as having a moderate level of social sustainability.

The scenario with the second highest level of sustainable development is Plan B of Case II, as it resulted in an annualized gross profit of $657,369/year and an average value of copper waste generation of 3.957×10^3 lbs/year over the 10-year time span of interest. Similar to Plan A of Case II, Plan B from Case II was also evaluated as having a moderate level of social sustainability.

Case recommendation

Each scenario evaluated has resulted in slightly improved regional sustainable development. The recommendation for scenario implementation is based on the scenario with the highest positive level of regional sustainable development. As was discussed above, Plan A from Case II was evaluated as being the most sustainable scenario, therefore it is recommended for implementation taking into account the

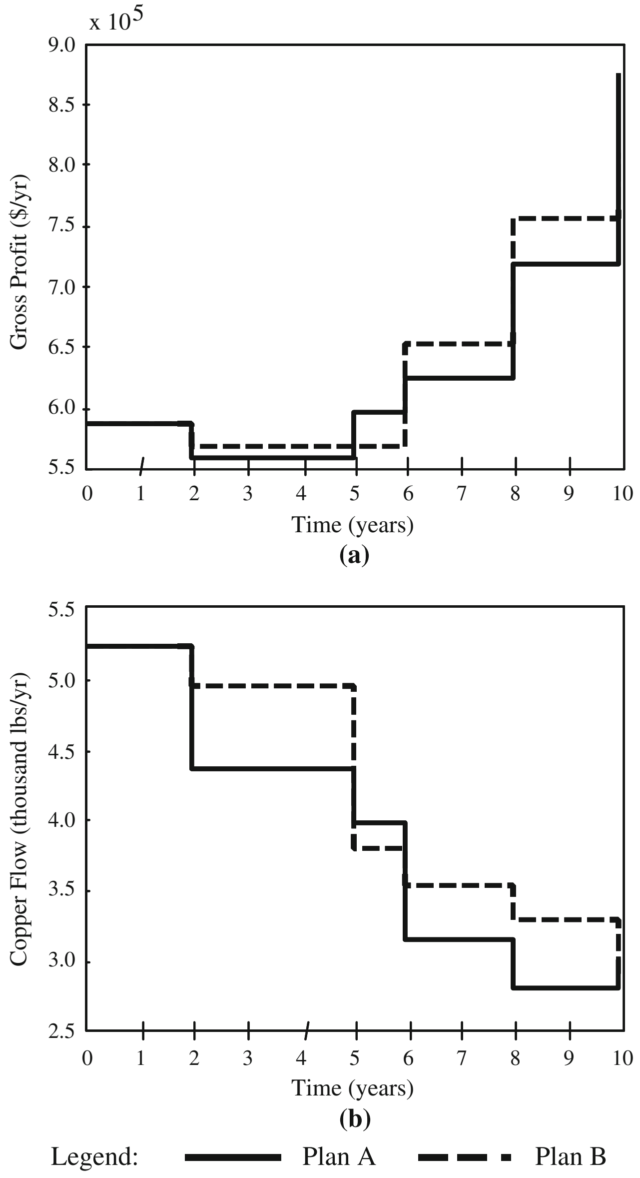


Fig. 11 Case II: overall zone analysis: **a** economic and **b** environmental

economic feasibility of its implementation, followed by Plan B of Case II. If neither of these scenarios can be implemented, it is encouraged that the entities within the industrial zone focus on the investment into further improving their internal P3 technologies, as in Case I, as it was found and shown in Fig. 9 that over time such an investment will result in improved economic and environmental sustainability.

The above case studies have implemented the modeling and analysis methodology in order to assess the regional industrial sustainability and evaluate the effect of future production options that will have on the zone's production and waste generation based on modified network inputs and modified supply chain connections. As such, the plan that is recommended is based on the path that each entity within the zone should follow into the future in order to improve the sustainable development of the overall industrial zone, in this example, Plan A of Case II.

Concluding remarks

Sustainable development looks to simultaneously improve the triple bottom lines of sustainability. The study of complex industrial zones involves many uncertainties, which arise directly from uncertain, incomplete, and imprecise data selection, use of inappropriate models, and/or lack of knowledge or information in addressing the problem of the sustainable development, thus making sustainability-focused analysis extremely difficult. Thus, in attempting to model and assess the sustainable development of an industrial zone, a methodology for the characterization and management of data uncertainty is necessary to provide more information and is vital for improved analysis capabilities.

This paper expanded on the principles of P2 and P3 and focused on utilizing the idea of collaborative P3 (CP3) to aid in decision-making toward sustainable development. Collaborative P3 (CP3) includes a system modeling and analysis methodology, which provides industrial decision-makers with the ability to assess the industrial units' state of sustainability, evaluate future production options, and aid in the selection of the production plan with the best possibility of working toward the sustainable development of not only a single unit, but also of the overall industrial zone.

Implementation of the methodology allows for the assessment of a company or zone's state of industrial sustainability and encourages collaboration between all entities involved in the product supply chain. The framework provides industrial forecasters with the ability to utilize the information gained from the analysis to assess the effect future industrial zone changes will have on the zone's sustainable development by way of evaluating future production options to determine the production paths with the most positive impact on not only their own sustainability, but also the sustainability of the overall industrial zone. Finally, to demonstrate the efficacy of the methodology, it was used in the evaluation of a series of case studies to address the issues of uncertainty in the study of the sustainable development of a complex auto-manufacturing focused industrial zone.

It is important to note that the CP3 based modeling approach is general and broad and therefore is applicable to a multitude of modeling scenarios. For instance, how one entity's changes affect the remainder of the entities within the zone and the zone as a whole or modeling the effect that impending regulations or policies will have on an industrial zone's production and waste generation. As such, future applications of the CP3 modeling approach can include the study of other types of uncertainties that arise in the study of industrial sustainability, including supply chain uncertainty, whether or not products will be shipped and supplied on time, at the quality level requested, etc. Furthermore, the above-mentioned unit, subsystem, and system models can be incorporated into an optimization scheme, in order to determine the network structure with the optimal economic, environmental, and social sustainability levels.

Acknowledgments This work is in part supported by NSF (CMMI 0730383 and DGE 9987598) and Michigan Department of Environmental Quality.

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