Chapter 12
Application of the Sequential Interindustry Model (SIM) to Life Cycle Assessment

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Introduction: LCA in Industrial Ecology

As an emerging science, industrial ecology needs to identify and develop appropriate quantitative methods (Koenig and Cantlon 1998, 2000; Seager and Theis 2002). One of these primary tools has been Life-Cycle Assessment (LCA). LCA is used for assessing the impacts of products, processes, services, or projects on the environment (Graedel and Allenby 2003). The expression life-cycle indicates a "cradle-to-grave" approach, beginning with a product's conception and continuing through to its ultimate recycling or disposal. Thus, a product's or process' lifetime includes (1) a raw materials acquisition phase, (2) a manufacturing, processing and formulation (3) a distribution and transportation phase (4) a use/re-use/maintenance phase (5) a recycling phase (6) and waste management (end-of-life) phase. LCA traditionally consists of four stages, (1) goal and scope (2) inventory analysis, (3) impact assessment, and (4) improvement analysis. In particular, Life Cycle Inventory (LCI) analysis describes those resources required and pollutants produced over the product's lifetime (Fava et al. 1991). Major benefits of LCA include: a systematic method to evaluate the overall material and energy efficiency of a system; the ability to identify pollution shifts between operations or media as well as other trade-offs in materials, energy, and releases; and a means to benchmark and measure true system improvements and reductions in releases (Owens 1997).

Two main methods exist for performing the life cycle inventory stage of an LCA study – Process LCA (PLCA) and Economic Input-Output LCA (EIO-LCA), each

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with its relative advantages and disadvantages (Hendrickson et al. 1997; Matthews and Small 2001). The recent development of hybrid models is aimed at gaining the advantages of both (Suh 2004). Another distinction among LCAs is classifying them as either attributional or consequential. An attributional LCA approach is what one thinks of as the traditional LCA – capturing the environmental properties over the life cycle of a product, process or project. In contrast, a consequential LCA approach describes the changes within the life cycle. Although IO models are considered intrinsically attributional based on the nature of the average industry data that typically supports them, the approach here is more akin to consequential LCA (Ekvall 2002; Ekvall and Weidema 2004).

Leontief Input-Output Models are the basis of EIO-LCA (Hendrickson et al. 1998; Joshi 2000; Matthews and Small 2001). The static Leontief model (Leontief 1966) can provide a useful tool in extending the boundaries of LCA, and defining them in a non-subjective way, by accounting for industrial activities indirectly as well as directly required in the production of goods. The result is a more comprehensive coverage of potential human health and environmental impacts that result from those activities (Duchin 1992; Lave et al. 1995; Hendrickson et al. 1998; Joshi 2000; Matthews and Small 2001). By using an EIO-LCA approach, the problem of subjective boundary definition is addressed by including industrial activities throughout the whole industrial system (Joshi 2000). The focus of an assessment shifts from a boundary issue to one that describes how a particular product being assessed is linked into the economy as a whole.

This chapter will focus on what we presently see as two limitations to EIO-LCA. First, neither traditional LCA nor the static Leontief IO model contains explicit temporal information, that is, describes in any detail how production activities associated directly or indirectly with a product, and its related impacts, economic or environmental, are distributed over time. For some products and processes, and certainly for many long-term capital projects, these activities and impacts, such as the ecological toxicity effects of persistent chemicals of concern, though transient, may be distributed over considerable periods of time. Moreover, the specific pattern of the distribution may be critical to evaluating its impact. Furthermore, EIO-LCA, by extending the boundaries within the industrial system, also extends the temporal boundaries of the analysis. Production activities indirectly related to a product may be carried out a considerable time before the product is completed (e.g., the production activities of mining iron ore that ultimately ends up in an automobile). Thus, temporal information is more important in EIO-LCA than in PLCA.

Second, traditional input-output models are interindustry *production* models. This provides little basis for describing impacts due to a product's subsequent use and retirement phases (Joshi 2000), either of which may generate the greater part of the product's lifetime environmental impact. For example, consider the gasoline, oil, tires and batteries that are consumed by an automobile during its use phase. EIO-LCA models provide a cradle-to-output gate analysis, when in fact a cradle-to-grave analysis is called for. Joshi (2000) has outlined a way in which the input-output model could be readily extended to account for the use phase and we will consider this issue in this chapter (see also Gloria 2000). We should note that with the extension of the IO model to the use and retirement phases the need for temporal-based information becomes even more pronounced.

The approach presented, utilizing the Sequential Interindustry Model (SIM) (Romanoff and Levine 1981), is intended to address a class of problems where the activities within and outside the life cycle are affected by a change within the life cycle of the product under investigation. It is structured around causal relationships, represented by a sequence of events originating from a decision at hand. SIM was originally developed to investigate the impact of transient economic events, such as a construction project (Levine and Romanoff 1989), the “hollowing out of a regional economy” (Hewings et al., 1998, 2001), or an earthquake (Okuyama et al. 2004). The life-cycle of a product, process, or project is such a transient event, possibly managed by formal planning techniques and tools such as the critical path method (CPM). This suggests that SIM might provide a useful extension of the EIO-LCA methodology.

While based on the static Leontief model, SIM is a dynamic system model that describes how the various indirect as well as direct inputs, outputs, and associated impacts of such events are distributed in time – information that the static Leontief model does not provide. SIM is mathematically formulated such that in the absence of temporal change (i.e., in steady state) it reduces to the static IO model, the important emergent dynamic properties that sculpt the framework of SIM disappear in the absence of temporal concerns.

The Importance of Temporal Information in EIO-LCA

In general, if we seek to justify employing a more sophisticated model, in this case a dynamic rather than static model, we must ensure that this additional effort makes a difference to the solutions we discover. How important is temporal information in LCA? As summarized by Udo de Haes et al. (1999a, b): “LCA essentially integrates over time. This implies that all impacts, irrespective of the moment that they occur, are equally included.” However, in practice LCA tools provide essentially a static description of the impacts of an existing product or process – a “snapshot” of environmental impact, where the snapshot is based on all that occurred over the time interval of the snapshot. (The same can be said for the static input-output model; it provides a “snapshot” of the economy.) The reason is primarily limitations of available data. Although by definition, the *Goal and Scope* stage of an LCA study determines the boundary of analysis, in practice, it is the Life-cycle Inventory (LCI) that ultimately determines the actual extent of the research. Although there may be temporal information available in some data, it is not true for all data. Historically, the immense task of collecting data to conduct a comprehensive LCA at best, defaults to a static analysis.

Yet, relying on the static model may not be enough to support the decision-making process to know that industry A on average annually emits B pounds of substance C to the environment per dollar of industry A's total output. The rate of production by industry A may vary considerably over the course of the year. The emission does not occur all at once at the completion of the production process. Rather, the emission rate of substance C may vary considerably over the production process. The environment may react in a decidedly non-linear way to increased concentrations of substance C. For instance, there may be a threshold concentration level below which substance C is harmless but above which it becomes a health problem. The concentration of substance C will be determined by its history of emission. This is further complicated if substance C itself may decompose at different rates as a function of average air temperature, or be dissipated at different rates at different times during the year due to wind speed or wind direction.

For these and other reasons, the rate and the specific time at which emissions and other disturbances are produced, and not simply their quantity, may be critical to evaluating their impact on the environment (Field et al. 2000); the loss of temporal information in the inventory phase of an LCA may limit the accuracy of the impact assessment and at a minimum long-term emissions should be inventoried separately from short-term emissions (Owens 1997; Hellweg and Frischknecht 2004). An input-output model dealing with time in an explicit manner could under these circumstances greatly enhance the role of input-output analysis in LCA.

When we move beyond the production phase alone to consider the whole life-cycle of a product, the need for temporal information is, if anything, even greater. Products and projects continue to demand resources and produce impacts during their use phases and in their retirement phases as well. These resources and impacts may be of a very different nature than those occurring during the production phase. They may vary seasonally, or be influenced by the age of the product or project. An input-output model dealing with time in an explicit manner could under these circumstances greatly enhance the role of input-output analysis in LCA.

Static and Dynamic Systems

Both static and dynamic IO models are concerned fundamentally with the structure of the interrelationships or interdependencies among variables and data of models of the system of concern. They differ, of course, in their treatment of time.

> A static model is one whose structural relationships do not contain time in any analytically meaningful way. By contrast, dynamic systems are those which do contain time-relationships among the relations of the variables in meaningful ways, i.e., in ways which could not be eliminated without affecting the solution to the system or eliminating the possibility of the solution (Kuenne 1963, p. 457).

The distinction between static and dynamic models is not simply the existence of time in a dynamic system and its absence in a static model. The use of a static model must still involve the interpretation of its solution "against time as a backdrop" (Kuenne 1963, p.15). That is, although typically not explicitly recognized or even ignored, time is a factor when implementing a static model. Comparative statics (Duchin 1998, p.123), as an example, involves what may be considered a sequence of 'snapshots" of successive equilibria. However, a fundamental difference between the two approaches is that a specific solution to a static system yields a single solution vector, whereas a specific solution to a dynamic system is "a set of such vectors linked in a path through time" (Kuenne 1963, p. 14), that is, a trajectory. A dynamic model, therefore, may have *more than one path* converging to the same (or different) equilibrium.

A static system can yield theorems about "the values of the variables only in a state of rest, or theorems about changes in the values of the variables only between two states of rest." In contrast, incorporating the notion of inter-period relationships, "a dynamic model contains the potential for the derivation of theorems concerning the values of the variables, or changes in those values, before the position of rest, or equilibrium has been attained" (Kuenne 1963, p. 14).

Dynamic LCA to assess long-term environmental impacts was first introduced by Moll (1993). In Moll (1993) static LCA approaches were found to be appropriate to compare and evaluate products under three conditions. First, the products should have relatively short life cycles, on the order of period of less than 5 years. In this case, the context that surrounds the product can be assumed as non-changing. Second, products should have stabilized consumption levels. Here, average values can be used to accurately describe input and output requirements. And third, products should remain static with regard to technologic or social changes in the life cycles considered. Essentially, the static life-cycle is relevant as a method of analysis for a context where the system is in steady-state.

Conversely, Moll (1993) concluded that the dynamic LCA approach is appropriate to compare and evaluate policy options that in essence the criteria are the antithesis of relatively short term product issues examined by static LCA. That is, dynamic LCA is appropriate to assess products with long life cycles (greater than 5 years), that involve substantial changes of consumption levels, and undergo changes in the applied technologies. Here the system context is not in steady-state and is possibly far out of equilibrium. The timing and changes in the use of materials and energy and their subsequent environmental repercussions are significant. The significance of the timing and rate of changes are important for assessing long-term results that ultimately influence policy options.

Moreover, Moll (1993) concluded that the static LCA methodology and the dynamic methodology did not change the rank order of design criteria of the products analyzed. However, additional insights gained by conducting dynamic LCAs of product alternatives that lead to policy options include:

The relevant choice of the integration period, that is, the rate the new technology be phased in and an old technology be retired.

The period required for environmental improvements. For example, the amount of time the policy option is to be implemented to achieve its reparation objectives.

The calibration of the trends in the absolute magnitude of relevant parameters to the environmental policy. That is, a context is established with outside forces, such as trends in national economic conditions or trends in larger sources that affect the dynamics of the policy examined.

The duration of the period to reach steady-state – how long will the policy option induce change, and what will the final state of that change.

Post the seminal contribution to the science of LCA by Moll (1993), Gloria (2000) applied aspects of temporal consideration put forth by Moll (1993). Inspired by the structural economics work by Duchin (1998) and interindustry models that incorporate the details of production sequences (Romanoff and Levine 1981; Levine and Romanoff 1989), Gloria (2000) presents a formulation of Sequential Interindustry Model (SIM) in an LCA context. Examining a case study of market penetration of an emerging technology, fuel cell electric vehicles (FCEVs), and its effects on the reduction of greenhouse gas emissions in the U.S. National Economy, Gloria (2000) presented a structured approach to examine the repercussions of the integration period. That is, an investigation was made of the rate the new technology, FCEVs, were to be phased in and for the old technology, internal combustion engine vehicles (ICEVs) to be retired. Other notable use of dynamics and LCA applied to the pulp and paper industry can be found in Ruth and Harrington (1997).

Sequential Interindustry Model (SIM)

Interindustry models describe the flows of goods (and services) in industrial systems. The traditional Leontief static input-output model represents the total output of an industrial system as

$$g = w + f \tag{12.1}$$

where:

g = total output vector,
w = intermediate output vector, and
f = final output vector.

The assumption of a linear production function leads to

$$g = Ag + f \tag{12.2}$$

where:

A = technical matrix.

While suppressed, time is implicit in the static input-output model. We treat time as a sequence of discrete intervals of finite length. The periodic economic input-output tables published by different countries fit this model, each new table being the next entry in a sequence. Thus, the values of **g**, **f**, **w** and **A** are based on measuring economic activity over some discrete interval of time, such as a year, and can change from one interval to the next. Equation (12.1) can be rewritten making this time dependence explicit,

$$g(t) = w(t) + f(t) = A(t)g(t) + f(t) \tag{12.3}$$

where t is an index of discrete time intervals. Equations of this type are referred to as comparative static models, producing what we will call a static temporal sequence. They provide, as noted, a sequence of 'snapshots' of the economy.

Equation (12.3), like Equation (12.2), provides an accounting of output; total output in interval t consists of intermediate output in interval t plus final output in interval t. It is a purely descriptive model of existing economic activity. However, in many applications we are interested in prescribing the specific total output **x** required to produce an arbitrarily specified quantity of final output **y** (Suh 2004, Ch. 3). It is this ability of the input-output model to account for all the linkages, and thus all the sources of environmental impact linked to a final output **y**, that makes it a valuable tool in LCA. Making the assumption that **A**, the technical matrix, is independent of scale, we rearrange Equation (12.2) and replace data-based outputs **g** and **f** by the application-specific outputs **x** and **y,** to obtain the Leontief inverse equation,

$$x = (I - A)^{-1} y = By. \tag{12.4}$$

Again, time is implicit. However, as noted, this is no longer a descriptive statement of 'annual' accounting. It is instead a prescriptive model, telling us what total output **x** must be produced in order to achieve the desired final output **y**. Making Equation (12.4) temporally explicit by writing

$$x(t) = B(t)y(t) \tag{12.5}$$

reveals its essentially static nature. **x**(t) is fully determined by **B**(t) and **y**(t); it is independent of **y** or **B** in any interval other than t. Thus, successive values of **x** are independent of each other. Similarly, there is no 'rule' relating the value of **B** (and thus of **A**) in interval t to its value in other intervals. Moreover, Equation (12.5) is correct only if it is true that the total output **x** required to provide for interval t's final output **y(**t) is itself entirely produced in interval t, though it will be numerically correct if the system is in steady-state. In general neither one of these conditions will be true, and the first condition is especially unlikely if the time interval under consideration is short compared to the times required by the various production activities. (It is precisely these relatively short time intervals that are needed, as described earlier, to evaluate environmental impacts.)

In fact, production requires time, and thus some of the intermediate output that ultimately is imbedded in one interval's final output will likely occur in previous time intervals. Put another way, total output in interval t is determined not only by final output for interval t but by future final output as well. An appropriate formulation must recognize that we are describing a dynamic system in which total output levels in different intervals are dependent on each other. To be consistent with Life Cycle Inventory (LCI) approaches (Suh 2004), while maintaining an explicit representation of time, a more accurate formulation of time dependence will be required.

In order to account for the time required by production activities the coefficients of the **A** matrix must describe not only what inputs are required by a producing sector but when those inputs are required in the production process. For simplicity, and because of its importance in modern day industrial systems, we will assume just-in-time (JIT) production modes. In just-in-time production, with no inventories and assuming no transportation delays, output from a supplying industry occurs in the same interval as it is required by the demanding industry. Duchin, (1998, p. 46) has noted the importance of adding engineering information to economic information in the development of structural economics (the field that includes input-output economics). SIM is an example of just this principle. We might describe this addition of production lead times as moving from a list of ingredients to a recipe, or as supplementing accounting information regarding what is needed to make the product with engineering information on the production process itself.

Again, we will make the assumption that **A** is scale independent. Utilizing the engineering information, the technical coefficient $\mathrm{a_{ij}(t)}$ is partitioned into $\mathrm{a_{ij}}(\mathrm{t}, \tau)$, $\tau = 0, 1, 2, 3, \ldots$, where τ measures in intervals the production lead time, and where $\Sigma_\tau\ \mathrm{a_{ij}}(\mathrm{t}, \tau) = \mathrm{a_{ij}(t)}$. Intermediate production then becomes

$$w(t) = \sum_{\tau=0}^{\infty} A(t, \tau)x(t + \tau), \tag{12.6}$$

and is determined by requirements of future output. In this article we will assume that the **A** matrix does not change over time (i.e., it is time invariant) so that $\mathbf{A}(\mathrm{t}, \tau) = \mathbf{A}(\tau)$, and Equation (12.3) becomes

$$x(t) = \sum_{\tau=0}^{\infty} A(\tau)x(t + \tau) + y(t). \tag{12.7}$$

In contrast to the comparative static system description of Equation (12.3), Equation (12.7) represents the production dynamics of the industrial system being modeled. It produces what we will call a dynamic temporal sequence. The model displays one of the characteristics of a dynamic system, its ‘memory’; output at one interval is linked to output at other intervals. The apparent non-causal structure of this model is explained by recognizing that in practice these future requirements would be either established future orders or estimates of future demand.

We can put Equation (12.7) into a more computationally convenient form through use of Z transform techniques (DeRusso et al. 1998). For discrete time sequences such as **y**(t),

$$y(z) = Z\{y(t)\} = \sum_{t=-\infty}^{\infty} y(t)z^{-t} \tag{12.8}$$

Taking the Z transform of Equation (12.7), we obtain

$$x(z) = A(z)x(z) + y(z), \tag{12.9}$$

with the corresponding inverse equation,

$$x(z) = (I - A(z))^{-1}y(z) = B(z)y(z) \tag{12.10}$$

Inverse Z transform techniques can then be used to determine the time sequence

$$x(t) = Z^{-1}\{B(z)y(z)\} = \sum_{\tau=0}^{\infty} B(\tau)y(t+\tau). \tag{12.11}$$

Thus, the total output at interval t is determined by the future as well as the present final output. Again, the future final product would in general be either orders or estimates.

SIM and Environmental Burden

Joshi (2000) has suggested a method for extending the static input-output model to account for environmental impacts associated with a total output vector through the use of environmental burden coefficients. For this purpose Joshi (2000) introduced the normalized environmental burden matrix **R,** with r_{kj} the kth environmental burden (e.g., carbon monoxide release, toxic chemical release, etc.) generated per dollar output of sector j, and the total environmental burden vector **e**, with e_k the kth environmental burden, where $\mathbf{e} = \mathbf{Rx} = \mathbf{RBy}$.

In the context of SIM, environmental burden is a dynamic concept. The emissions associated with the production of output in interval t occur over a number of preceding intervals, in a similar fashion to the inputs. ε(t), the emissions in interval t, can be expressed as:

$$\varepsilon(t) = \sum_{\eta=0}^{\infty} P(\eta)x(t+\eta), \tag{12.12}$$

where $\mathbf{P}(\eta)$ weighs the contribution of future output to present emissions.

Environmental burden in interval t, **e**(t), is in turn dependent on the accumulation of previous emissions, where physical phenomena such as dispersal and disintegration of emitted materials in the air, water, or land are accounted for by appropriately weighting the past. The environmental burden in interval t is

$$e(t) = \sum_{s=0}^{\infty} W(s)\varepsilon(t-s) = \sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} W(s)P(\eta)x(t-s+\eta) \tag{12.13}$$

where **W**(s) is a diagonal matrix of weighting values. To put this in the form of the Joshi model we let $\mathbf{R}(s,\eta) = \mathbf{W}(s)\mathbf{P}(\eta)$, and

$$e(t) = \sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} R(s,\eta)x(t-s+\eta) = \sum_{\tau=0}^{\infty}\sum_{s=0}^{\infty}\sum_{\eta=0}^{\infty} R(s,\eta)B(\tau)y(t-s+\eta+\tau) \tag{12.14}$$

Applying SIM to LCA: Theory

We now consider the application of SIM to LCA. Up to now our development of SIM has focused, as with the EIO, on the production phase of a product's life. However, we have already noted that operation and maintenance of a product, as well as its retirement, require resources. Gasoline consumption by automobiles, electricity use by factory equipment, and periodic painting of bridges are but three examples of resources required during the use phase of products. All of these contribute to environmental burden. Furthermore, the problem of attributing environmental burden to either production or use phase is complicated because with the exception of final product, the use phase of one product is part of the production phase of another. The two burdens are not independent.

Equation (12.14), similar to the Joshi model, attributes all burden to the production phase. In dealing with vectors of total product this is necessary. If we account for the environmental impact due to the burning of oil in electricity production as part of the environmental burden of the electric power industry, we cannot include this oil usage as part of the environmental burden of the petroleum industry without double counting burdens. However, this presents difficulty if we wish to develop the LCA of a specific product and include its use phase. To overcome this difficulty we will follow a suggestion of Joshi (2000), and deal with the use phase of the product by treating it as a hypothetical industry sector producing a final product. The output of this sector is a used product. This allows us to frame the use phase of a product as if it were part of the production phase of a used product. The inputs required to produce a used product are the product when it was new plus all the resources it required during its use phase. For example, the "production" of a 10-year old car requires as its inputs a new car, 10 years prior to the outputting of the used car, plus 10 years of gasoline, oil, tires, batteries, etc.

We will therefore consider the environmental burden generated by all direct and indirect production activities associated with one unit of final output from hypothetical sector n in interval t_0 after a use phase of σ intervals. Thus, our final output is

$$y^*(t) = 1_n \delta(t - t_0), \tag{12.15}$$

where $\mathbf{1}_n$ is a vector of all 0s except for a 1 as element n, and $\delta(t - t_0) = 1$ when $t = t_0$, and equals 0 otherwise. The total output attributable to this one unit of final output is

$$x^*(t) = \sum_{\tau=-\infty}^{\infty} B(\tau) y^*(t + \tau) = B(t_0 - t) 1_n \tag{12.16}$$

with resulting environmental burden

$$e^*(t) = \sum_{s=0}^{\infty} \sum_{\eta=0}^{\infty} R(s, \eta) x^*(t - s + \eta) \tag{12.17}$$

Applying SIM to LCA: Computer Results

In order to demonstrate the effect of temporal variation on the environmental burden generated by a product over its production and use phases we have carried out three numerical examples using SIM. All of these examples correspond to an identical five sector static model. This was done to highlight the additional information that is provided by a dynamic model. The first three sectors of the model describe the entire economy with the exception of the industry whose product we wish to assess. The fourth sector describes the industry whose product we wish to assess while a fifth sector represents the "production" of a used product of that type. Our model included two different environmental burdens.

All our examples correspond to the same static model with the following **A** and **R** matrices describing the five sectors and two burdens.

A Matrix

0.24	0.18	0.12	0.24	300.00
0.24	0.30	0.12	0.30	250.00
0.30	0.24	0.18	0.12	200.00
0.06	0.06	0.06	0.00	1,000.00
0.00	0.00	0.00	0.00	0.00

R Matrix

27.74	31.21	24.27	31.21	8,718.83
16.76	25.14	27.93	22.35	10,535.44

The resulting environmental burden vector, $\mathbf{e}^*$, corresponding to the production and use of one unit of the product being assessed is

$\mathbf{e}^*$ Vector

172,302.32
142,818.51

In our SIM versions we will assume the product is produced in interval 0 and retired after ten intervals of use. Given values of $\mathbf{y}^*(\mathrm{t})$, $\mathbf{A}(\tau)$, $\mathbf{P}(\eta)$ and $\mathbf{W}(\mathrm{s})$, chosen so as to be consistent with the static model, we will then compute $\mathbf{e}^*(\mathrm{t})$, the environmental burden history corresponding to the production and use of that one unit. In order to do this we needed to calculate $\mathbf{B}(\tau)$. This was done by utilizing the power series form of the Leontief inverse, that is

$$B(z) = (I - A(z))^{-1} = \sum_{k=0}^{\infty} (A(z))^k \qquad (12.18)$$

and truncating the summation at some appropriate value of k. A comparison to $\mathbf{B} = (\mathbf{I} - \mathbf{A})^{-1}$ in the examples we ran indicated that our approximations captured on the order of 97% of the total production.

We will vary two things in our three examples, the duration of the production processes and the rate at which the emissions degrade. Again, this will be done in such a way as to not create any change in the static IO model. Thus changes in $\mathbf{W}(s)$, accounting for degradation rates, will require compensatory changes in $\mathbf{P}(\eta)$ in order that the resulting $\mathbf{R}$ matrix in the static model is unaffected.

Example 1. Long Production Phase, Slow Emissions Degrading

In this example the first four sectors have production processes requiring six intervals. Sector 5 has a "production" process of ten intervals, corresponding to the use phase of the product being assessed. The emissions producing the two burdens degrade at rates of 20% and 25% per interval respectively. Figure 12.1 shows the history of the emissions burdens for this example.

Example 2. Short Production Phase, Slow Emissions Degrading

This example differs from Example 1 by having production processes that require only two intervals. Everything else is identical to Example 1. Figure 12.2 shows the history of the emissions burden for this example.

Example 3. Short Production Phase, Quick Emissions Degrading

This example differs from Example 2 by having emissions that degrade at rates of 60% and 62.5% per interval respectively. $\mathbf{P}(\eta)$ is modified accordingly. Everything else is identical to Example 2. Figure 12.3 shows the history of the emissions burden for this example.

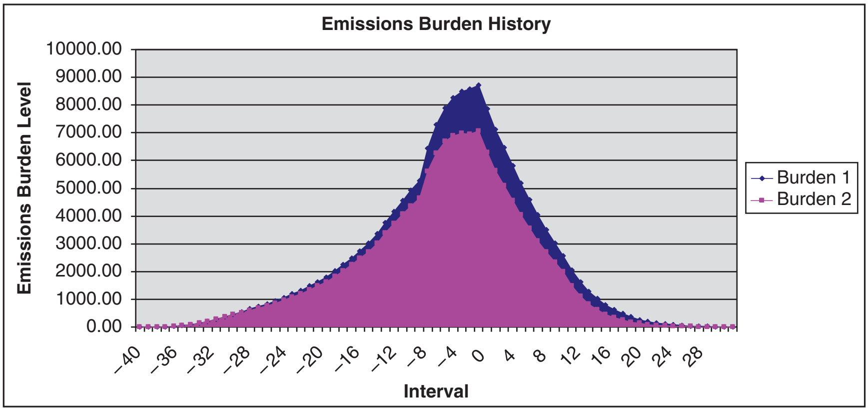

Fig. 12.1 Emissions Burden History for Long Production Phase, Slow Emission Degradation Case

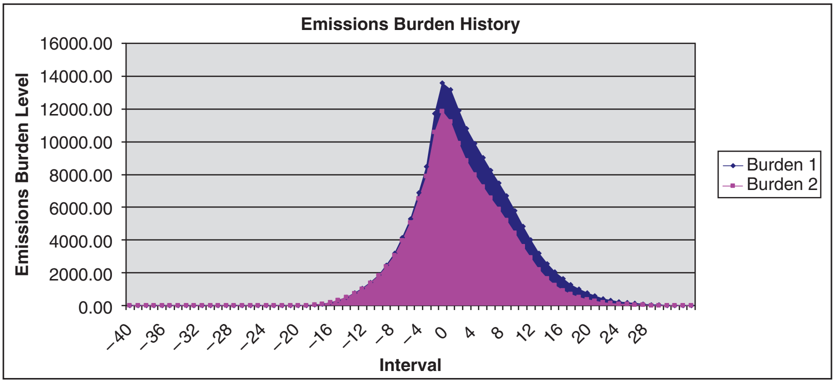

Fig. 12.2 Emissions Burden History for Short Production Phase, Slow Emissions Degradation Case

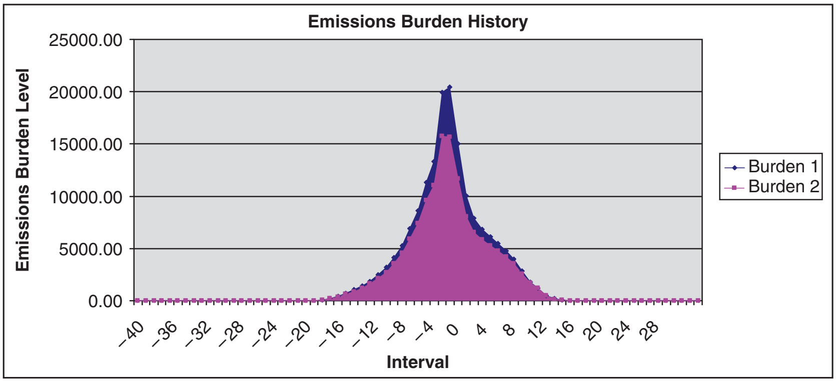

Fig. 12.3 Emissions Burden History for Short Production Phase, Quick Emissions Degradation Case

Udo de Haes et al. (1999a) notes that LCA, as presently practiced, essentially integrates over time. The use of static models is one aspect of this integration procedure. As noted, all three of our dynamic examples correspond to the identical static case, that is, in all the examples the areas under the curves are identical. However, if our concern with environmental burden includes concern for peak values or if the impact assessment phase of LCA recognizes the existence of threshold values, the three examples are dramatically different.

Discussion

Input-output models are likely to play an increasingly larger role as a tool in future LCA applications – both disciplines are grounded in the pursuit of understanding the intricacies of the industrial complex. Input-output approaches have to a fair extent ameliorated LCA issues of truncated boundaries and greatly assisted in the task of identifying the interconnections of the multitude of indirection that are present in the global economy, if not a mere appreciation and awareness of the task. Thus use of input-output provides a large existing database for LCA practitioners. However, LCA has been traditionally applied to products, revealing the limitations of the coarseness of the IO datasets that support the models. The level of aggregation in input-output models limits the ability to compare products within the same sector of the economy. This is a data limitation issue (Lave et al. 1995; Joshi 2000), one that we have not addressed in this chapter. (SIM is, if anything, even more demanding of data.) Moreover, traditionally IO models are cradle-to-output gate models, unable to assess downstream effects. Suh (2004) and others have addressed this issue through hybrid approaches.

Despite these shortcomings the application of the static IO model in LCA continues. However, neither traditional LCA nor the static Leontief IO model contain explicit temporal information, that is, describe in any detail how the production activity associated directly or indirectly with a product, and its related impacts, economic or environmental, is distributed over time.

In this chapter we introduce SIM in order to broaden the discussion of what IO models are, and how they can be applied in an LCA context. The relevance of SIM in this context is multi-fold: it is based on the fundamentals of the static IO model that capture the interdependencies of complex system; as a dynamic model it can express the intricacies of the order of occurrence of events in this broad structure; and it can be easily reduced back to the static model to examine whether a dynamic implementation brings value to understanding the system of concern. Two major additions have been made to the SIM to enhance its contribution to LCA. First, we have expanded the SIM model beyond a cradle-to-gate implementation typical of the static IO model. And second, static IO approaches are solutions to life cycle inventory issues related to LCA under the premise of integrating economic activity and human health and environmental repercussions over an infinite time horizon. Here, a more explicit relationship to such repercussions is made, specifically issues related to rates of production and emissions relative to persistence in the environment.

The IO model developed was applied to a simple five-sector production economy. The scenarios revealed that a potentially significant perspective can be gained by the addition of temporal information. Specifically, this is an understanding not only of the totality of emissions, but also indicators such as when the emissions will occur, peak values of the resulting emission burdens, and length of time thresholds are exceeded. This provides a more accurate assessment of the accumulative characteristics and associated impact profiles (e.g., exposure and dose characteristics that would describe human health repercussions). To fully examine and assess environmental and human health repercussions, the associated impact assessment models will need to be able incorporate this new temporal information.

Life cycle thinking and the associated tools of PLCA and EIO-LCA provide a necessary component for comprehensive assessment. However, post assessment, temporal information required for implementation strategies is the essential for planners. By adding temporal information, issues of the following can be examined more thoroughly: the appropriate integration period for replacement technologies; the amount of time the policy option is to be implemented to achieve its objectives; how long will the policy option induce change, and what will the final state of that change. The snapshot perspective provided by static LCA is one step in selecting preferred options. By providing temporal information, the solution set is more thoroughly understood by introducing the influences of the constraints of real world conditions. Additionally, of course, LCI information that contains spatial characteristics will also greatly enhance the analysis. In the real world, it is not just a matter of getting from point A to B, it also matters when and how you get there – when and where materials are procured and delivered, finances are secured and committed, and people employed and compensated, and practical technological solutions solved and proven practical, and as important, the ramifications of garnering these resources in time and space as they affect the environmental as well as, economic and political that they are interdependent upon.

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