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A COMMENT

on "Functions, Commodities And Environmental Impacts In An Ecological-economic Model"

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A comment on “Functions, commodities and environmental impacts in an ecological-economic model”

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Abstract

In a recent paper in this journal, Suh (2004) presented a model combining life cycle assessment (LCA) with input-output analysis (IOA); termed “integrated hybrid LCA”. In this paper, we discuss various issues relating to the theoretical and practical use of the integrated hybrid LCA approach. In particular, the interpretation of the downstream feedback term, C^d, is discussed from both a theoretical perspective and a practical implementation perspective. In this paper, two interpretations of C^d are suggested depending on the particular LCA database used. If the LCA database is designed for a demand on the functional unit only, then it is argued that the C^d term is negligible in most applications. If the LCA database is compatible with an arbitrary demand, then it is argued that in most cases the consistent use of the C^d term implies excessive data requirements that are not justified by the potential gains. We then discuss further issues relating to the integrated hybrid LCA model and combining LCA and IOA in general.

Keywords

Life cycle assessment (LCA); Input-output analysis (IOA); Integrated hybrid analysis; Hybrid LCA; Mixed units

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1 Introduction

It is generally acknowledged that environmental impacts occurring outside of the system boundary in life cycle assessment (LCA) models may lead to a significant under estimation of total environmental impacts (Lave et al., 1995; Suh et al., 2004). It is believed that this error can be reduced by combining economic input-output analysis (IOA) and LCA; this approach is commonly referred to as hybrid LCA. The current approach in hybrid LCA is to purchase items outside the process based system boundary of the LCA from economic sectors; often referred to as a "tiered hybrid LCA" (Suh et al., 2004). An "integrated hybrid LCA approach" has also been postulated where the economy purchases items from the LCA. This latter approach is the focus of this paper.

Suh (2004) presents an overdue theoretical development of a fully integrated hybrid LCA model. In this paper we discuss various issues relating directly to the approach presented by Suh (2004) and the reader is referred to that paper for a detailed discussion of the integrated hybrid LCA approach. A recent review of hybrid LCA can be found in Suh et al. (2004).

To simplify the text, Suh (2004) is simply referred to as Suh. Reference to equations from Suh begin with an S; for example (S20) represents equation (20) in Suh. The notation from Suh is retained in this paper.

2 Interpretation and use of C^d

Suh (2004) expresses the integrated hybrid LCA approach mathematically as (compare with (S25)),

$$\begin{pmatrix} \tilde{A}_* & -C^d \\ -C^u & I - A'_{***} \end{pmatrix} \begin{pmatrix} \tilde{x} \\ x \end{pmatrix} = \begin{pmatrix} \tilde{y} \\ 0 \end{pmatrix} \quad (1)$$

where $\tilde{A}_*$ is the physical flow matrix for the process LCA, A'_{***} is the adjusted input-output (IO) matrix, C^d and C^u are the downstream and upstream "cutoff" terms, $\tilde{x}$ is the output of the LCA, x is the output of the economy, and $\tilde{y}$ is the demand on the functional unit of the LCA. The environmental impacts of the hybrid LCA are given by

$$\bar{q} = \tilde{B}\tilde{x} + B'_{***}x \quad (2)$$

where $\tilde{B}$ is the environmental intervention produced by the LCA system and B'_{***} is the environmental intervention produced by the economic system. The reader is encouraged to refer to Suh (2004) for further elaboration on the individual terms.

In practice, LCA databases[1] contain incomplete system descriptions. The upstream cutoff term, C^u, refers to the parts of the life cycle that are not incorporated in a specific LCA database because there environmental impact is thought to be negligible (e.g. Baumann and Tillman, 2004, pp. 82–83). Studies have shown that a significant portion of

[1] In this paper, the term "LCA database" refers to the conventional LCA data collected in physical units from process based information. If the system boundary of the LCA has been extended to include economic data then "hybrid LCA database" would be used. Further, the term database does not refer to "commercial databases", but rather LCA databases in general.

the environmental impacts may be neglected due to premature cutoff (Lave et al., 1995; Lenzen, 2001; Norris, 2002). As is discussed below, the upstream cutoff term, C^u, has a clear interpretation in the context of LCA; however, the downstream cutoff term, C^d, requires a closer examination.

For the discussion to follow it is necessary to extract the equations from (1). The output of the economy is given by

$$x = (I - A'_{***})^{-1} \underbrace{C^u \tilde{x}}_{1} \tag{3}$$

This shows that the output of the economy is due to the information "left out" of the processes in the LCA database and subsequently added in monetary terms as "purchases" from within the economy; the amount purchased is shown by the underbrace, $C^u \tilde{x}$.

The output of the LCA, $\tilde{x}$, can be expressed as

$$\tilde{A}_* \tilde{x} = \tilde{y} + \underbrace{C^d \underbrace{(I - A'_{***})^{-1} \underbrace{C^u \tilde{x}}_{1}}_{2}}_{3} = \tilde{y} + \underbrace{C^d \underbrace{x}_{2}}_{3} \tag{4}$$

This shows that the output of the LCA increases due to a demand from other parts of the economy (term 3). Term 1 was discussed above as the LCA requirements from the economic system. Term 2 is the output of the economy resulting from the demand 1, compare with (3). Therefore, term 3 is the increased demand on the LCA system resulting from the economic system (term 2).

From these equations it can be seen that if $C^u = 0$ then the IO model makes no contribution to the overall output. This implies that the LCA has included all possible commodity flows and requires no external purchases from the IO model; that is, to avoid cutoff the system boundary extends to infinity. Generally, fewer and smaller terms in C^u mean that the LCA is increasingly detailed.

The C^d term is of particular interest; to date, most hybrid LCA studies have put $C^d = 0$. If $C^d = 0$ then the output from the LCA is unchanged by the economic model; this model is commonly called "tiered hybrid LCA" (Heijungs and Suh, 2002; Suh et al., 2004).

When $C^d \neq 0$, then inspection of (4) shows that C^d distributes the output of the economy to the different LCA processes. Despite the terminology "downstream cutoff term" it is unlikely that the elements of C^d arise from the selection of the economic system boundary. Typically, the product for which the LCA is being performed would be a part of the economy and represented in the IO data (compare with double counting in hybrid LCA).

As mentioned, C^d distributes the output of the economy to the different LCA processes. It is questionable whether a standard LCA is designed to handle a demand on processes other than the functional unit (Guinée et al., 2002; Heijungs and Suh, 2002). This will depend on the particular LCA database, and before applying the integrated hybrid LCA, the LCA practitioner needs to verify that the LCA is designed for an arbitrary demand[2].

[2] Arbitrary demand implies a demand on any process, in particular, processes other than the functional unit.

The example LCA developed by Suh was designed around a demand on the functional unit; 1000 pieces of toast. The extra demand on the LCA system due to the downstream cutoff term is

$$C^d x = (0.10, 0.25, 0, 0, 0.13)' \tag{5}$$

That is, the economy places a demand of 0.1kg of Steel, 0.25kWh of Electricity, no Toasters, no Pieces of Toast, and 0.13kg of Waste Disposal Services back onto the LCA system. The functional unit is no longer demanded, but rather other processes in the LCA system are demanded.

From a practical point of view, some LCA databases may be consistent for arbitrary demands. For consistency, separate processes need to feed back to other processes. This feedback can be seen in Suh's toaster example for the Steel and Electricity processes; each process requires input from the other process. In contrast, the Use of Toaster process in Suh's example purchases other processes, but other processes do not purchase it. This is usually justified as the size of the feedback would commonly be negligible. It is this later feedback onto the functional unit that is not conventionally incorporated into LCA studies.

Given the above arguments, what role does C^d have in hybrid LCA? Whether an LCA database is designed for an arbitrary demand is likely to be debated amongst the LCA community. The remainder of this paper discusses how the C^d term would be used in both cases: First, an LCA designed for a demand on the functional unit only is considered. Second, an LCA designed for an arbitrary demand is considered. In reality, many LCAs would lie between these two extremes.

2.1 The standard LCA approach

Consider an LCA that is designed for a demand on the functional unit only. As is shown in (5) the C^d matrix used by Suh, (S30), places a demand on processes other than the functional unit[3]. If the C^d matrix is to place a demand on the functional unit only, then it must be modified to have non-zero values in the row corresponding the functional unit and zeros elsewhere.

The non-zero values in C^d correspond to purchases from the economic sectors on the functional unit of the LCA. For instance, in the toaster example, the employees producing a given commodity in some arbitrary economic sector require slices of toast for lunch coming from the particular type of toaster described in the LCA. Further, all of the economic activity in this system is stimulated by the cut-off purchases from the economic system.

If it is assumed that each sector uses 0.01 slices of toast for each dollar of output then

$$C^d = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{6}$$

[3]The following arguments do not seek to pre-judge the approach taken by Suh with his hypothetical example of a toaster. Suh's toaster example is retained in this paper for demonstrative purposes.

In this case, the increased demand on the LCA system due to the IO model is

$$C^d x = (0, 0, 0, 0.0632, 0)' \tag{7}$$

That is, an increased demand of 0.0632 slices of toast (which is probably quite generous considering this value comes from economic activity stimulated by the life cycle of one type of toaster). The new impact of CO_2 using this C^d is 27.2369kg. It is worth noting that if C^d is taken as zero, then the impact of CO_2 is 27.2352kg. Given that the difference occurs at the fifth significant figure it is highly likely that this difference is well below the errors in the LCA and IO models[4].

In the above example the contribution from the C^d term was negligible and some thought will reveal that it is likely to be negligible for most LCAs on consumer products. That is, the purchases of the economy on the functional unit that are stimulated by the LCA itself are likely to be negligible to the life cycle impacts of the product. This can be confirmed by considering some simple examples; a paper cup, a refrigerator, a car, and so on.

However, if the LCA was to model the life cycle of a major structural shift in an industry then it is possible that the C^d term could become important. For instance, in modeling the use phase of a power station, the purchases of the economy back onto the power station may become an important quantity. In this case, it is likely other modeling techniques would be heavily incorporated; for instance, modifications of economic technology in IOA. Further, one would have to question the choice of functional unit if feedbacks endogenously increase the functional unit.

This section has argued that if the LCA is designed for a demand on the functional unit only, then the likely contribution from the C^d term is negligible. Further, from a practical point of view, collecting the required data to determine C^d would be somewhat troublesome. It is suggested that if the LCA is designed for a demand on the functional unit only, then the LCA practitioner should put $C^d = 0$.

2.2 General hybrid LCA models

To consider the case when an LCA is designed to handle an arbitrary demand requires a different approach. An LCA which is designed for arbitrary demands and with consistent feedbacks is more related to IOA in mixed units; both physical and monetary units. Many IO studies have used mixed units, particularly when studying indirect effects of energy consumption (Bullard and Herendeen, 1975).

The mathematical abstraction of LCA and IOA into matrix notation leads one to think that LCA and IOA have strong links, however, on a conceptional level, LCA and IOA have many differences. A key difference is that LCA considers the consequences of *one* particular functional unit, while IOA is interested in the flows between *all* economic sectors (where sectors are analogous to processes in the terminology of LCA). In this sense IOA captures all possible feedbacks and indirect effects for an *arbitrary* demand instantaneously through $(I - A'_{***})^{-1}$.

[4] Note that in the example by Suh, 30kg of CO_2 is released in the fully integrated model using the C^d from (S30); a 10% difference to the system with $C^d = 0$.

While these differences may seem subtle, they are particulary evident in the data collection phase. An LCA practitioner collects all the data for the processes instigated by a demand on the functional unit until the system boundary is reached. These processes may feedback onto other processes (as for Electricity and Steel in Suh's toaster example). The system boundary encompasses the most relevant processes to the functional unit. In contrast, when collecting the data for an IO table, the starting point is to determine all flows between *all* sectors. No one sector is selected as of more interest than another. The system boundary includes all economic transactions in an economy. In this way, IOA automatically encompasses all possible feedbacks within the industry aggregation used.

Considerable insight is gained into different hybrid LCA approaches by rewriting the integrated hybrid LCA model as in (S23), repeated here for convenience,

$$\begin{pmatrix} \tilde{A}_{*} & -C^d \\ -C^u & I - A'_{***} \end{pmatrix} \begin{pmatrix} \tilde{g} \\ g_{***} \end{pmatrix} = \begin{pmatrix} \tilde{f} \\ f_{***} \end{pmatrix} \tag{8}$$

It is possible to construct the LCA data so that only unit values appear on the diagonal of $\tilde{A}_{*}$; to this end, let $\tilde{A}_{*} = I - \tilde{A}_{**}$. This allows (8) to be rewritten in the standard form used in IOA,

$$g = Ag + f \tag{9}$$

where $g = (\tilde{g}, g_{***})'$, $f = (\tilde{f}, f_{***})'$, and

$$A = \begin{pmatrix} \tilde{A}_{**} & C^d \\ C^u & A'_{***} \end{pmatrix} \tag{10}$$

Recall, that in this section it is assumed that the LCA is compatible with arbitrary demands.

Table 1 shows the A matrix in (10) for the example of the toaster in Suh. Note that several manipulations have been performed to the data presented by Suh. First, the Use of Toaster column has been normalized to have a one on the diagonal (this also requires a modification of the environmental intervention matrix, $\tilde{B}$). Second, the rows and columns of the matrix have been reordered; the reasons for this will become apparent below. Note that the C^d matrix (S30) is used (top right hand corner) and not the C^d matrix presented in (6) since the LCA system is assumed to be compatible with arbitrary demands.

Equation (9) has been studied in detail since its conception by Leontief (1936). The element A_{ij} represents the purchases of sector/process j from sector/process i for one unit of output from sector/process j. Alternatively, each column, $A_{\cdot j}$, gives the inputs into each process/sector for one unit of output of that column. This interpretation can be seen in Table 1. Each column of the matrix gives the inputs from the various LCA processes and IOA sectors. For example, to produce 1 Toaster (second column) requires 2kg of Steel, 0.1kWh Electricity, \$0.1 of Construction and \$0.1 of Other.

By considering the first five columns in Table 1 it is easy to interpret C^u (matrix on the lower left corner) as the purchases of the LCA from the economic sectors. These purchases from the economy are outside of the system boundary of the LCA database, but may lead to a significant environmental impacts.

Of more interest is an analysis of the economic sectors and the interpretation of C^d. Consider the last six columns in Table 1; these are the economic sectors. The first five elements in each column are the purchases of the IO sectors from the LCA, the remaining elements are the purchase of the IO sectors from other IO sectors (the standard IO table). For example, the Manufacturing sector purchase 0.05kg of Waste Disposal, 0.01kg of Steel, and 0.08kWh of Electricity from the LCA, plus various purchases from other sectors in the economy. Each of the purchases of the economic sectors from the LCA must be subsequently subtracted from the IO table, A'_{***}, to avoid double counting.

From a practical point of view, the columns of C^d are essentially an LCA of each of the economic sectors. For each economic sector, the LCA practitioner is required to determine the quantity the sector purchases from each LCA process. Suh proposes using an IO table at the commodity-commodity level, which essentially implies doing an LCA of each commodity in an entire economy. Even for an LCA database and an IO table of small size the data requirements to construct C^d are considerable.

Even if it was feasible to construct C^d, it is likely it would make negligible contributions to environmental impacts. The accuracy of an LCA is more dependent on the core LCA data rather than the C^d term which in most cases will only contribute to environmental impacts after several feedbacks. The economy must be stimulated through C^u before C^d can contribute to environmental impacts[5]. The reader is referred to articles by Round (2001) and Sonis and Hewings (2001) for discussions of feedback effects in IOA.

By expressing the integrated hybrid LCA as in Table 1 it becomes straight-forward to show the relationship with the method proposed by Suh and IOA in general. The ordering of the processes in Table 1 allows a combination of the IO table with the core LCA data. Consider if the IO table, A'_{***}, was disaggregated to include Electricity and Steel as separate sectors, but in physical units. That is, the LCA processes of Steel and Electricity are merged into the IO table. This division of A is shown in Table 2.

In Table 2 the IO table (bottom right corner), A'_{***}, is now in mixed units. The LCA of the toaster, including Production, Use, and Disposal, purchase items from the expanded IO table. This is the approach that was performed by Joshi (2000), except Joshi only used one sector representing construction of different types of petrol tanks and the IO table was the standard USA IO table in monetary units. Model II from Joshi (2000) is analogous to the integrated hybrid LCA with $C^d = 0$ and using only one sector.

A criticism of the approach by Joshi (2000) is the handling of use and disposal phases of the life cycle (Suh et al., 2004), however there is no reason why the use and disposal phases can not be further disaggregated into the IOA framework as is shown in Table 2 and essentially performed by Suh (in fact, Nakamura and Kondo (2002) explicitly model end-of-life). In fairness, the disposal phase in any LCA has many of the same weaknesses as the approach by Joshi (2000), particularly for products with a long life cycle; technological change may drastically change the method of disposal. In many cases, the contribution of end-of-life to some environmental impacts may be negligible in comparison to other effects (Lenzen, 2001).

Another study which expanded an IO table to perform an LCA is the Waste Input-Output (WIO) model (Nakamura and Kondo, 2002). In the WIO model, Nakamura and Kondo (2002) expanded the Japanese IO table to include waste and waste treatment sectors. The primary objective of the study was to compare different waste treatment

[5]It is worth noting that in the structural path analysis performed by Suh, his Table 5, the C^d term does not contribute to any of the important paths.

policies. In the WIO model, a demand is placed on both the economic system and the waste LCA system. Further, both upstream and downstream feedbacks are incorporated. Conceptually, the WIO model is more related to an expansion of an IO table (c.f. Joshi, 2000), then an LCA purchasing items outside the process system boundary from an IO table (c.f. the integrated hybrid LCA model).

The above discussion has shown that the integrated hybrid LCA approach proposed by Suh has many similarities to mixed unit IOA and the hybrid approach used by Joshi (2000). Perhaps the biggest difference is the level of data aggregation. IO data is an aggregation of many industries in broad sector definitions. LCA data is usually a disaggregation of individual production processes on very specific products with very specific functions.

The possibility of using mixed unit IO tables for conducting hybrid LCA studies has some appeal. Detailed IO tables in mixed units may reduce the data requirements for many hybrid LCA studies and reduce the many assumptions resulting from monetary units. Due to the data collection methods used in constructing IO tables, feedback loops to other economic sectors are more likely to be consistently represented. The primary goal of combining LCA with economic IOA is to increase the system boundaries of an LCA and reduce data collection; for this to work, it is beneficial for the LCA and IOA data to be consistent.

3 Discussion and Conclusion

It is apparent from a variety of studies that the cutoff from LCA studies can neglect a significant contribution to the impacts (Suh et al., 2004). Consequently, it is important to include these impacts; possibly through the use of economic IOA.

On one level there is merit in studying the ideal theoretical framework for an integrated hybrid LCA approach. On another level, it must be remembered that LCA is a practical tool. A disadvantage of a standard tiered hybrid LCA (with $C^d = 0$) is the extra data collection required. For instance, if the IO table from the USA is used (roughly 500 sectors) with an LCA with 500 processes then calculating the C^u term requires 250,000 matrix elements; many of these will be zero, but a thorough study needs to verify this. Further, other technical issues arise such as using the appropriate valuation in the IO table, double counting, and so on. Given these issues, a theoretical assessment of the integrated hybrid LCA approach should address the issue of data availability and collection. Regardless of the interpretation of the C^d term, it is evident that data will be an issue.

This paper has shown that the interpretation of the C^d term depends on whether the particular LCA is designed for a demand on the functional unit or is designed for an arbitrary demand. If the LCA is designed for a demand on the functional unit alone, then in most cases, the contribution of the C^d term to environmental impacts will be negligible. If the LCA system is compatible with arbitrary demands, then each column of C^d is essentially an LCA of each sector in the IO table. The data collection in this case would be considerable, and the likely benefits minimal.

The integrated hybrid LCA model proposed by Suh has many similarities with the approach presented by Joshi (2000). Since most OECD countries regularly construct IO data, the use of IO tables in mixed units may minimize the data collection requirements for LCA databases and lead to a more consistent merging of IO and LCA data.

For the LCA practitioner, this paper has argued that the standard approach of performing a tiered hybrid LCA (with $C^d = 0$) is consistent from a theoretical point of view. Further investigations are required to determine the applicability of the integrated hybrid LCA approach proposed by Suh. A key issue is how to correctly use the C^d term and what can be gained from its use. It was suggested that an alternative approach is the method used by Joshi (2000), but using mixed units for the IO data.

References

Baumann, H., Tillman, A.-M., 2004. The hitch hiker's guide to LCA: An orientation in life cycle assessment methodology and application. Studentlitteratur, Lund.

Bullard, C. W., Herendeen, R. A., 1975. The energy cost of goods and services. Energy Policy 3, 268–278.

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., de Bruijn, H., van Duin, R., Huijbregts, M., 2002. Handbook on life cycle assessment. Operational guide to the ISO standards. Kluwer Academic Publishers, Dordrecht.

Heijungs, R., Suh, S., 2002. Computational structure of life cycle assessment. Kluwer Academic Publications, Dordrecht, The Netherlands.

Joshi, S., 2000. Product environmental life-cycle assessment using input-output techniques. Journal of Industrial Ecology 3 (2-3), 95–120.

Lave, L., Cobas-Flores, E., Hendrickson, C., McMichael, F., 1995. Using input-output analysis to estimate economy-wide discharges. Environmental Science and Technology A 29 (9), 420A–426A.

Lenzen, M., 2001. Errors in conventional and input-output-based life-cycle inventories. Journal of Industrial Ecology 4 (4), 127–148.

Leontief, W., 1936. Quantitative input and output relations in the economic system of the United States. The Review of Economic Statistics 18 (3), 105–125.

Nakamura, S., Kondo, Y., 2002. Input-output analysis of waste management. Journal of Industrial Ecology 6 (1), 39–63.

Norris, G. A., 2002. Life cycle emission distributions within the economy: Implications for life cycle impact assessment. Risk Analysis 22 (5), 919–930.

Round, J. I., 2001. Input-output analysis: Frontiers and extensions. Palgrave Publishers Ltd., Ch. Feedback effects in interregional input-output models: What have we learned?, pp. 54–70.

Sonis, M., Hewings, G. J. D., 2001. Input-output analysis: Frontiers and extensions. Palgrave Publishers Ltd., Ch. Feedbacks in input-output systems: Impacts, loops and Hierarchies, pp. 71–99.

Suh, S., 2004. Functions, commodities and environmental impacts in an ecological-economic model. Ecological Economics 40 (4), 451–467.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. Environmental Science and Technology 38 (3), 657–664.

$A =$

	Use	Prod	Disp	Steel	Elec	Ag	Min	Man	Con	Fin	Other
Use	0	0	0	0	0	0	0	0	0	0	0
Prod	0.001	0	0	0	0	0	0	0	0	0	0
Disp	0.001	0	0	0	0	0	0	0.05	0	0	0.03
Steel	0	2	0	0	0.5	0	0.015	0.01	0.05	0	0
Elec	0.001	0.1	0	0.5	0	0	0.05	0.08	0	0	0.01
Ag	0	0	0	0	0	0.3	0.1	0	0	0	0.1
Min	0	0	0	0.1	0.01	0.1	0.2	0.2	0.1	0	0.2
Man	0	0	0	0.1	0.1	0.2	0.2	0.3	0.2	0.1	0
Con	0	0.1	0	0	0	0.1	0.1	0.2	0.1	0.2	0.2
Fin	0	0	0	0	0	0.1	0	0	0.2	0.2	0.2
Other	0	0.1	0.1	0	0	0.1	0.2	0.1	0.2	0.2	0.1

Table 1: The matrix A including both the LCA processes and IOA sectors, compare with (10). Note that the Use of Toaster process has been normalized and the LCA processes reordered. The abbreviations are: Use: Use of Toaster (piece); Prod: Production of Toaster (unit); Disp: Waste Disposal Services (kg); Elec: Electricity (kWh); Ag: Agriculture; Min: Mining; Man: Manufacturing; Con: Construction; Fin: Financial Services; Other: Other products and services.

$A =$

	Use	Prod	Disp	Steel	Elec	Ag	Min	Man	Con	Fin	Other
Use	0	0	0	0	0	0	0	0	0	0	0
Prod	0.001	0	0	0	0	0	0	0	0	0	0
Disp	0.001	0	0	0	0	0	0	0.05	0	0	0.03
Steel	0	2	0	0	0.5	0	0.015	0.01	0.05	0	0
Elec	0.001	0.1	0	0.5	0	0	0.05	0.08	0	0	0.01
Ag	0	0	0	0	0	0.3	0.1	0	0	0	0.1
Min	0	0	0	0.1	0.01	0.1	0.2	0.2	0.1	0	0.2
Man	0	0	0	0.1	0.1	0.2	0.2	0.3	0.2	0.1	0
Con	0	0.1	0	0	0	0.1	0.1	0.2	0.1	0.2	0.2
Fin	0	0	0	0	0	0.1	0	0	0.2	0.2	0.2
Other	0	0.1	0.1	0	0	0.1	0.2	0.1	0.2	0.2	0.1

Table 2: The data is the same as in Table 1, but the core LCA data, Steel and Electricity, has been moved into the IO table.

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1/2004	Erlend Sletten Arnekleiv & Stig Larssæther	*Grønn innovasjon - perspektiver, metoder og utfordringer: En litteraturstudie*

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