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INPUT-OUTPUT AND HYBRID LCA

Framework for hybrid life cycle inventory databases: a case study on the Building for Environmental and Economic Sustainability (BEES) database

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Abstract
Purpose In an effort to develop a whole building Life Cycle Assessment (LCA) tool, National Institute of Standards and Technology (NIST) is transforming new bottom-up Building for Environmental and Economic Sustainability (BEES) data into a hybrid database in which the strengths of both bottom-up and top-down approaches can be combined. The objective of this paper is to describe the framework and the process under which the hybrid BEES database is being built, with an emphasis on its accounting structure. This paper can support other efforts to build hybrid Life Cycle Inventory (LCI) databases.
Methods The BEES hybridization utilizes the most detailed supply and use tables (SUTs)—known as item-level data—focusing particularly on the construction sectors. First, the partial SUTs at the item level are constructed and connected to standard SUTs that describe the rest of the economy, which is then followed by balancing and "redefinition." Second, item-level environmental data are compiled and then also balanced and redefined, which completes the compilation of the bi-resolution SUTs with environmental data. Third, the bi-resolution SUTs are integrated with the BEES data that have been converted into matrix form. Because the completely rolled out BEES technology matrix involves a significant number of products, the integration prioritizes the product groups that are potentially the most significant contributors to the LCIA results for buildings.
Results This step-by-step procedure will enable the creation of a hybridized BEES database, combining the strengths of both the bottom-up, process-based data and the top-down, input-output data with enhanced resolution. The benefit of hybridization at the database level—as opposed to at the individual LCA study level—is that whole-building LCA users can adopt the hybrid BEES approach, with its benefit of a more complete system definition, without the training or effort that would be required to construct a hybrid system from scratch. In addition, reformulation of new BEES data into a matrix structure better facilitates the parametric LCA application that is central to NIST's vision to develop a tool for assessing the sustainability performance of energy technologies and systems in an integrated building design context.
Conclusions There are currently a number of initiatives being organized to implement a hybrid approach at the LCI database level. In laying out the methodological framework for efficiently transforming an existing LCI database into a hybrid database, this paper can support future development of hybrid LCI databases.

Keywords BEES · Building industry · Hybrid · Input–output · LCI database

1 Introduction

Recently, the U.S. Department of Commerce's National Institute of Standards and Technology (NIST) initiated the Metrics and Tools for Sustainable Buildings project, which contributes to the agency's Net-Zero Energy, High-Performance Buildings Program. Its objective is to develop, integrate, and apply

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measurement science to assess the sustainability performance of energy technologies and systems in an integrated building design and operation context. With its sustainability performance measurement methods and tools, NIST is taking a lead role in providing guidance to the building community on the life cycle environmental and economic performance of specific building types designed to meet and exceed current building energy codes. NIST recognizes that reliable, consistent Life Cycle Inventory (LCI) data is important to the success of this effort.

NIST has developed and maintained the Building for Environmental and Economic Sustainability (BEES) database that contains LCI, Life Cycle Impact Assessment (LCIA), and cost results for building products. With the current move from building product Life Cycle Assessments (LCAs) to whole building LCAs, NIST recognizes (1) the need to close large gaps in product categories by broadening the product coverage available in the database and (2) the need to embed the BEES processes in the context of a broader economy, minimizing truncation, and improving consistency in system boundary selections. Addressing both needs, NIST is adopting the integrated hybrid approach for structuring its whole building LCA database. Transforming new BEES data relating to building energy technologies into a hybrid LCI database will yield LCAs for whole buildings designed to meet a range of energy codes. At the same time, this transformation will help reduce the truncation problem and—more importantly—the heterogeneity across products, thereby improving consistency. We will refer to the hybrid LCI database being developed for whole buildings and that embeds BEES processes as the "hybrid BEES" database in this paper.

Besides the NIST initiative to hybridize BEES, a few other LCI database providers, including the Ecoinvent Center, are discussing or planning LCI database hybridizations (Weidema 2011). However, the literature currently lacks discussion about the framework of hybrid LCI databases. The objective of this paper is to describe the framework and the process under which the hybrid BEES database is being built, with an emphasis on its accounting structure. This paper can help support other efforts to build hybrid LCI databases.

This paper is organized as follows: "Section 2" describes a number of key methodological issues pertinent to the hybridization of BEES. "Section 3" introduces a step-by-step approach to building the hybrid BEES database. "Section 4" discusses the expected outcome and recommendations for hybrid LCA database building.

2 Methods

2.1 Hybrid approach

LCA methodology has often been described as a dichotomy between bottom-up and top-down approaches (Lave et al. 1995; Hendrickson et al. 1998). It should be also noted, however, that the complementary nature of the two approaches has been recognized in the LCA community since the early 1990s, and the two have often been used in combination through hybrid approaches (Moriguchi et al. 1993; Joshi 1999; Matthews and Small 2000; Lenzen 2002; Nakamura and Kondo 2002; Suh and Huppes 2002; Heijungs and Suh 2002; Suh et al. 2004; Finnveden et al. 2009; Suh 2009). Applications of hybrid approaches have also become more frequently reported in the literature (Bright et al. 2010; Chang et al. 2010; Kofoworola and Gheewala 2008; Lin 2009; Peters et al. 2010a, b; Sharrard et al. 2008; Reich-Weiser et al. 2010; Wiedemann et al. 2011).

The hybrid approach combines the advantages of both bottom-up and top-down approaches—namely the use of higher-resolution, process data (bottom-up) and the use of well-defined, regularly updated statistical data without truncation (top-down) (Suh et al. 2004; Suh and Huppes 2005). Under a generalized LCI framework, the pure process approach is on one end, the input-output approach is on the opposite end, and in between is a whole spectrum of hybrid approaches (Suh 2004). A hybrid approach could therefore be tailored to be a pure process LCA with only a small input–output portion or vice versa. As a result, the hybrid approach generally reduces the uncertainty of existing pure process-based or pure input–output-based systems; it helps reduce truncation error in the former and increases the resolution of the latter (Suh et al. 2004).

Three different hybrid approaches are distinguished in the literature, namely tiered, input–output-based, and integrated hybrid approach (Suh et al. 2004). In the tiered hybrid approach, which is the simplest form among the three, cutoffs of a pure process LCI are estimated using rolled-up[1] input–output (IO) LCA data (Moriguchi et al. 1993; Suh and Huppes 2002). The input–output hybrid approach partially increases the resolution of the IO LCA data by using additional information to disaggregate the data (Treloar 1997; Joshi 1999). Finally, the integrated hybrid approach mutually links the physical unit matrices used in LCA (Heijungs 1994; Heijungs and Suh 2002) with the input–output matrices in a single technology matrix (Suh 2004; Reich-Weiser et al. 2010) (for a comparison among hybrid approaches, see Suh et al. 2004; Suh and Huppes 2005; Wiedmann et al. 2011).

[1] The term "rolled-out" LCI in this paper refers to the elementary data underlying an LCI that show the exchanges of intermediate products and direct emissions by unit processes (or sectors). It is generally represented as a set of matrices including the technology matrix and the direct environmental exchange matrix. Ecoinvent uses the term, "unit process raw data" instead. Similarly, the term, "rolled-up LCI" refers to calculated LCIs, for which Ecoinvent uses the term, "cumulated results."

In prior studies, hybrid approaches have been applied to a single product system or research question. The hybrid approach, however, can also be applied at a database level, enabling much broader access to hybrid LCA. Once an LCI database has been properly hybridized—i.e., truncated supply chain links are connected to the background economic system represented by the input–output data—lay users of the database can benefit from a more complete system definition without having to acquire the necessary knowledge and skills needed to construct a hybrid system on their own.

Among the three hybrid approaches discussed earlier, the integrated hybrid approach is particularly suited for hybridization at a database level. By merging both physical and monetary unit descriptions of the system in a single technology matrix, the integrated hybrid approach preserves as much as possible detailed physical unit data. Furthermore, any improvements or changes made on one process are immediately passed on to all connected processes, enabling efficient system-wide updates and management. Finally, some existing public LCI databases such as Ecoinvent are already structured in a matrix form following Heijungs (1994) and Heijungs and Suh (2002), and, for those databases, the integrated hybrid approach would be a natural choice.

For this study, the resulting hybrid BEES database should be able to assess different scenarios for building energy systems. Such an analysis requires the ability to calculate LCA results due to changes in the parameters of a technology matrix—a task for which the features of the integrated hybrid approach become particularly useful.

2.2 Supply and use framework

Input–output data from statistical offices often come as supply use tables (SUTs) (the terms “tables” and “matrices” are used interchangeably in this paper). SUTs are the natural format for this information because the industries from which the underlying data are collected understand best which products they buy and sell, while they do not necessarily know from which industry their purchases are coming or to which industry their products are going (Stone et al. 1963; Konijn 1994). Likewise, environmental emission data are generally collected at the industry level rather than at the commodity level.

Because an industry may produce multiple commodities, the question then is how to assign environmental impacts to each commodity. This problem is essentially the same as the allocation problem in LCA but on a different scale. In the field of input–output analysis, a consistent mathematical representation has been developed to convert the SUTs to commodity-based information, which can then be used to formalize the allocation calculus in LCA (Suh et al. 2010). Three models are widely used to convert the SUTs to analytical tables: commodity–technology, industry–technology, and by-product technology models (Miller and Blair 1985; Konijn 1994). Suh et al. (2010) related these approaches to system expansion and partitioning allocation in LCA and proved that both commodity–technology and by-product technology models are functionally equivalent to the supply and use formulation proposed by Heijungs and Suh (2002).

In this particular study, we are using a more detailed level of supply and use data (known as item-level data) for the construction sectors, in addition to standard industry-level supply and use data for the rest of the economy. The term “item” in the tradition of US input–output table compilation refers to the basic building blocks used to compile standard SUTs. One industry or product in a standard SUT may consist of several to over a dozen item levels. For instance, a standard industry in the US SUT, “Nonresidential commercial and health care structures” consists of eight item-level industries including “New office buildings, including financial buildings,” “New hospitals,” “New health—special care buildings,” “New medical buildings,” “New multi-merchandise shopping,” “New food and beverage establishments,” “New warehouses,” and “New other commercial structures.”

As discussed in Suh et al. (2010), unit process-level LCIs can also be accommodated using the supply and use framework. We let the standard IO supply matrix, $V^{\mathrm{S}} = \left\{v_{ji}^{\mathrm{S}}\right\}$, show the amount of product i, regardless of the level of resolution, produced by the standard-level industry j, and the use matrix, $U^{\mathrm{S}} = \left\{u_{ij}^{\mathrm{S}}\right\}$, show the amount of product i purchased by the standard-level industry j, both of which are expressed in monetary unitsThe index i here covers the products of all three levels of resolution: (standard) industry, item and process.

Likewise, we denote the item-level supply matrix as $V^{\mathrm{I}} = \left\{v_{ki}^{\mathrm{I}}\right\}$, which shows the production of product i by item-level industry k, and the item-level use matrix as $U^{\mathrm{I}} = \left\{u_{ij}^{\mathrm{I}}\right\}$, which shows the purchases of product i by item-level industry k. Finally, we denote the process-by-product supply matrix as $V^{\mathrm{P}} = \left\{v_{li}^{\mathrm{P}}\right\}$, which shows the production of product i by process l, and the product-by-process use matrix as $U^{\mathrm{P}} = \left\{u_{il}^{\mathrm{P}}\right\}$, which shows the purchase of product i by process l. If the rolled-out unit process is already allocated, the process-by-detailed product part of V^{P} would be a diagonal matrix.

2.3 Estimation of cutoffs

The cutoff flows of an LCI database, including any data gaps from upstream supply chains, become the bridge that connects the process and the input–output systems. Therefore, the estimation of cutoffs plays a central role in determining the overall quality of the hybridization. According to the ISO standards, all cutoff choices should be clearly documented (ISO 2006), and such documentation is indispensible for compiling a reliable connection between the process-based and the input–output-based systems. Nevertheless, in practice, some cutoffs are not documented, and, for those missing flows, alternative estimations of cutoffs are needed.

One of the most promising approaches to reliable estimation of cutoff flows is the financial balancing approach. For any given unit process, all inputs in monetary terms plus the value added equals the total output in monetary value. The input–output table provides a useful reference on the range of value added by each sector. In other words, if $\sum_i u_{il}^{\mathrm{P}} \times p_i + w_l < \sum_i v_{li}^{\mathrm{P}} \times p_i$ for process l, where p_i is the price of the product i, and w_l is the value added estimate of process l based on its corresponding sector in the input–output accounts, the input requirement of the process is likely to be deficient. The sum of the monetary input requirements of such a process can be broken down into relevant input product groups and compared with the input structure of the corresponding sector in an input–output table to find out which particular inputs are likely to be missing. This approach was, to the best of our knowledge, first proposed in the literature by Marheineke et al. (1998).

2.4 Integration of the hybrid SUTs

We denote the integrated supply matrix V and the integrated use matrix U such that

$$V = \begin{pmatrix} V^{\mathrm{P}} \\ V^{\mathrm{I}} \\ V^{\mathrm{S}} \end{pmatrix}, \quad U = \begin{pmatrix} U^{\mathrm{P}} & U^{\mathrm{I}} & U^{\mathrm{S}} \end{pmatrix}$$

The item-by-process and product group-by-process parts of U^{P} correspond to the upstream cutoff matrix, in other words, missing inputs, in the original formulation of the integrated hybrid approach by Suh (2004). These parts show the cutoffs made by the LCA system that are linked to either an item-level or standard industry-level product in the input–output system, and they are therefore sparse but nonzero. The product-by-item part of U^{I} and the product-by-industry part of U^{S} corresponds to the downstream cutoff matrix in Suh (2004), which can be set to zeros without significantly affecting the system (see Peters and Hertwich 2006; Suh 2006). The integrated supply matrix V is generally a strict block diagonal matrix with zero matrices for off-diagonal blocks because the unit process, item-level industry and standard industry-level industry each supplies only its respective product level.

The overall accounting framework for hybrid BEES construction is summarized in Table 1. The first column of block matrices in the matrix U in the table, which is comprised of "Detailed product use by unit process," "Cutoffs linked to item-level products," and "Cutoffs linked to standard products" matrices, corresponds to U^{P}, and the second and third columns of block matrices correspond to U^{I} and U^{S}, respectively. Likewise, the first row of block matrices in the matrix V in the table, which is comprised of "Supply by process" and two zero matrices, corresponds to V^{P}, and the second and third rows of block matrices correspond to V^{I} and V^{S}, respectively. The integrated supply and use matrices can now be converted to analytical tables, if needed, using standard supply and use calculi. Derivation of the hybrid technology matrix, A, using the integrated SUTs will not be discussed here but can be found in Suh et al. (2010). Once U and V matrices are compiled as described in this paper, the rest of the calculation can be performed following Suh et al. (2010), which uses the same notations.

2.5 Overall calculation of LCIs

Once the technology matrix A and the allocated environmental coefficient matrix E are derived following Suh et al. (2010), the hybrid LCIs can be calculated as $E(I-A)^{-1}$, where I is an identity matrix. Alternatively, hybrid LCIs can be derived using the system expansion method by $B(V'-U)^{-1}$, where B is the total environmental flow matrix. If needed, a certain combination of the two calculi is also possible (see Suh et al. 2010, for details). For the sake of convenience, the coefficient form of the technology matrix is shown using concatenated matrices broken down into three different resolutions:

$$\begin{pmatrix} A_{\mathrm{P-P}}^{\mathrm{P}} & A_{\mathrm{P-I}}^{\mathrm{I}} & A_{\mathrm{P-S}}^{\mathrm{S}} \\ A_{\mathrm{I-P}}^{\mathrm{P}} & A_{\mathrm{I-I}}^{\mathrm{I}} & A_{\mathrm{I-S}}^{\mathrm{S}} \\ A_{\mathrm{S-P}}^{\mathrm{P}} & A_{\mathrm{S-I}}^{\mathrm{I}} & A_{\mathrm{S-S}}^{\mathrm{S}} \end{pmatrix}$$

The subscripts indicate the exchanges from one level of resolution to another. For instance, $A_{\mathrm{I-P}}^{\mathrm{P}}$ represents a segment of A^{P} that shows the item-level product inputs to processes.

These calculations will produce cradle-to-gate LCIs for all products in the context of the U.S. economy, which include intermediate products that are not part of the final database. In this case, final hybrid LCIs can be selected by extracting the relevant columns of the resulting matrix.

3 Step-by-step approach to hybridizing BEES

This section illustrates the step-by-step process under which the hybrid BEES database is being developed. The whole process can be summarized in seven steps (Fig. 1).

Table 1 Overall accounting framework for hybridization of BEES

	Detailed product	Item-level product	Standard product	Unit process	Item-level industry	Standard industry	Final demand	Total
Detailed product				Detailed product use by unit process	(Detailed product use by item-level industry)	(Detailed product use by standard industry)		
Item-level product				Cut-offs linked to item-level product	Item use by item-level industry	Item use by standard industry	Final demand on items	
Standard product				Cut-offs linked to standard products	Standard product use by item-level industry	Standard product use by standard industry	Final demand on standard products	
Unit process	Supply by unit process							
Item-level industry		Supply by item-level industry						Total output by item industry
Standard industry			Supply by Standard industry					Total output by standard industry
Value added		Value added	Value added					Total value added
Total	Total supply of detailed products	Total supply of items	Total supply of standard products					

The overall accounting framework follows that of the standard supply and use framework except that it uses three different levels of resolution and mixed units. Each column of block matrices in U and each row of block matrices of V corresponds to one of the submatrices, U^{P}, U^{I}, U^{S}, V^{P}, V^{I}, and V^{S} described in the "Section 2.4"

3.1 Comparability check

When using two databases together, regardless of whether they are of process origin, input–output origin or both, it is necessary to verify whether they are compatible in terms of their methodology and assumptions as well as in the completeness of their underlying data. For instance, even among process LCI databases, underlying methods and assumptions on, for example, allocation, treatment of durable goods and temporal system boundaries, may differ from each other, potentially causing inconsistencies. Two databases sharing the same methodological framework may still be incompatible if there is a material difference in completeness of the underlying data. Discrepancies in completeness between databases may stem from differences in the magnitude of cutoffs and deficiencies in data as well as in the number of environmental flows considered.

In this study, the Comprehensive Environmental Data Archive (CEDA) database (Suh 2005, 2010) is selected as the input–output database to be integrated with BEES. We compared the following issues between the CEDA and BEES approaches to LCI development with respect to their compatibility:

- Allocation methods
- Cutoff criteria
- Treatment of capital goods
- Base year
- Coverage of environmental flows

The results of the compatibility check are summarized is Table 2.

BEES employs various allocation methods, including mass-based, energy-based, and economic value-based allocation as well as system expansion (Lippiatt 2010), whereas

Fig. 1 Steps to construct hybrid BEES database

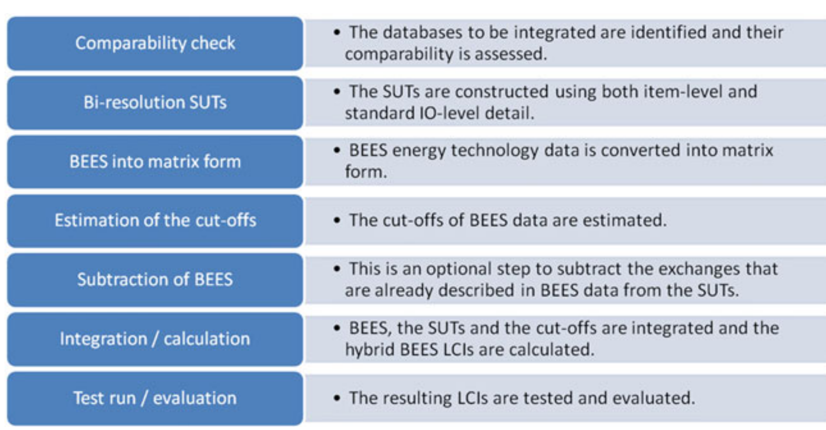

Table 2 Compatibility check between BEES and CEDA

	BEES energy technologies	CEDA
Allocation methods	Mass, energy, economic and system expansion	Economic, system expansion or a mixture of the two
Cutoff criteria	Mass, energy and economic value	N/A
Treatment of capital goods	Excluded	Included
Base year	Late 2000s–early 2010s	1998 (ver. 3), 2002 (ver. 4)
Coverage of the environmental flows	1,500 (previously 236) flows	1,344 flows (ver. 3), 2,591 flows (ver. 4)

CEDA uses economic value-based allocation, system expansion or a combination of the two. For the most part, the differences in allocation methods employed by the two databases are not expected to cause a material difference in the results. For instance, BEES applied energy-based allocation to refinery products, while CEDA performed economic value-based allocation. Nevertheless, energy content and economic value among refinery products are aligned relatively well, although there are specific cases where the two diverge. Therefore, the difference in allocation methods for refinery products between the two databases seems to have a minor influence on the overall compatibility.

The use of mass-based allocation for BEES LCI development, however, may potentially lead to a material incompatibility as mass and economic value are not strongly correlated. The main construction industry product category that is affected by the use of mass-based allocation are wood products and other products using wood products. To the extent that wood-based products are not among the energy technologies for which BEES data are being collected for whole building LCAs, potential compatibility issues are limited.

BEES LCIs use three cutoff criteria: mass, energy, and economic value. The use of the economic value of inputs as a cutoff criterion is particularly interesting in the context of hybridizing BEES, as it provides useful insight into the financial balancing approach employed in this study to estimate cutoffs. As one objective of this study is to close the cutoff gaps in BEES LCIs via the hybrid approach, the difference in cutoffs does not necessarily impose any incompatibility problems.

BEES follows the general guidance of the ISO LCA standards, which note that "manufacture, maintenance and decommissioning of capital equipment" shall be part of the initial system boundary (ISO 1998; clause 5.3.3.). In this respect, BEES and CEDA are, in principle, compatible. In practice, however, capital equipment generally is excluded in the final system boundary for BEES LCIs because it fails to meet cutoff criteria. Capital goods can be accounted for in the hybrid BEES database through the cutoff estimation described earlier.

The base years of BEES and CEDA appear to overlap quite well, as neither uses data more than 10 years old. A difference in the number of environmental flows between databases can raise some compatibility concerns. When databases are combined, the more complete database tends to contribute more to the end results than the less complete database, creating an unwanted bias. The original BEES database includes 236 environmental flows and the CEDA database includes 1,344 flows for version 3 (base year 1998) and 2,591 for version 4 (base year 2002). Comparing the original BEES with CEDA version 3, we found that 198 environmental flows are common to both databases, 38 flows are only in BEES and 1,163 flows are only in CEDA. The 38 flows that were identified only in BEES were not in CEDA due to a number of reasons, including different classification of flows.

In order to assess the potential incompatibility issues due to the difference in the coverage of environmental flows, LCIs of four construction sectors were calculated and characterized for three impact categories—global warming (GWP100), ozone layer depletion (ODP steady), and human toxicity (HTP100)—and the collective contributions from the unmatched flows were quantified. The result is shown in Table 3.

Although the large number of unmatched flows between BEES and CEDA may suggest incompatibility between the two databases, it is shown that the flows commonly included by both databases are the most important ones when characterized. For the global warming impact category, common flows represented 99.5–99.8%, showing that the 1,163 flows that are only in CEDA contributed less than 0.5% of the total. For ozone layer depletion, unmatched flows represented a more significant portion, ranging from 3.5% to 7.9% of the total. The unmatched flows for human toxicity contributed less than 1.7% in the construction categories considered (see Table 3).

Recently, such gaps become even smaller as the new BEES data for the hybrid database contain about 1,500 environmental flows. Overall, there were some minor incompatibility issues identified, but these issues do not appear to be significant enough to make hybridization infeasible. Such compatibility checks are useful to better understand the limitations of the hybrid BEES database.

Table 3 Importance of unmatched flows

	Global warming (GWP100)				Ozone layer depletion (ODP steady)				Human toxicity (HTP100)			
	NR1	NR2-4	NAA	NRGHA	NR1	NR2-4	NAA	NRGHA	NR1	NR2-4	NAA	NRGHA
Common flows	99.5%	99.8%	99.6%	99.7%	94.5%	94.7%	96.5%	92.1%	98.3%	98.8%	98.3%	98.3%
Only in BEES	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Only in CEDA	0.5%	0.2%	0.4%	0.3%	5.5%	5.3%	3.5%	7.9%	1.7%	1.2%	1.7%	1.7%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

NR1 new residential construction 1 unit, *NR2-4* new residential construction 2–4 units, *NAA* new addition and alteration construction, *NRGHA* new residential garden and high rise apartment construction

3.2 Construction of bi-resolution SUTs

Construction of the SUTs follows the standard procedure described in Horowitz and Planting (2006). There are 1,355 item-level products associated with construction sectors in the USA, including 42 building types. The official U.S. input–output table uses a mixed-technology model that involves redefinition and an industry–technology model (Horowitz and Planting 2006).[2] We follow the same redefinition procedure used by BEA. As described earlier, the process results in four matrices: V^{I}, V^{S}, U^{I}, and U^{S}.

In addition, data on environmental flows need to be collected for the item-level products. We utilize diverse data sources, including direct environmental flows from unit process LCIs, literature, available statistical data, and emission factors. The resulting draft environmental flow-by-industry matrix is then balanced and adjusted based on the constraint that the sum of each direct environmental flow across all the item-level industries that belong to a standard IO industry equals the corresponding environmental flow of the standard IO industry. The results are environmental flow per item-level and standard industry-level matrices.

3.3 Formation of technology and environmental matrices of BEES

The unit process-level, raw data for BEES energy technologies is converted into matrices to better facilitate the hybridization process described earlier. There are a few thousand unit processes in the completely rolled out data of the new BEES tool. This data includes information on upstream processes from commercial and non-commercial LCI databases. Likewise, the BEES environmental flow data is converted into direct environmental flows by unit process format for subsequent integration.

3.4 Estimation of the cutoffs

We employed a four-step approach to estimate cutoffs. First, existing documentation on cutoffs employed in developing BEES LCIs is used to help compile cutoff flows. Second, we identify key processes for which hybridization should be prioritized. Estimating cutoffs for all processes is not cost effective. Using standard contribution analysis (see e.g., Suh

[2] The term, "redefinition" is used by the Bureau of Economic Analysis (BEA) of the U.S. Department of Commerce to refer to the practice of manually moving certain outputs from a sector in a supply matrix and corresponding inputs to that sector in a use matrix to the industry where the output is produced as the primary product. It is done in an attempt to mimic the commodity–technology model without generating any negatives in the technology coefficient matrix (see Suh et al. 2010 and Horowitz and Planting 2006 for details).

2005) on the bi-resolution input–output table, the major contributing products to the 42 building types are identified, and corresponding processes in BEES energy technology LCIs are selected for an initial estimation of the cutoffs. Third, for the selected processes, price data are collected for inputs, and the financial balance approach is applied to locate potential cutoff flows. As described earlier, BEES uses not only mass and energy but also the economic value of inputs to a process as cutoff criteria. Such price information in BEES is very helpful in compiling cutoff data. Fourth, the compiled cutoff data are integrated into the U^{P} matrix.

3.5 Subtraction of the BEES portion from the SUTs

The exchanges of products represented by the BEES unit process data are, in principle, included in the bi-resolution SUTs. Subtracting the part of the exchanges already represented in the process domain can enhance the specificity of the IO information (see Appendix in Suh 2004). It should be noted, however, that the inclusion of the process data in the IO domain does not lead to double counting in the LCI results. The IO data represent an average of a sector. Therefore, by subtracting the process part from the IO part, the IO part can be better specified as an average of the remaining part of the sector without the processes represented in the process domain. For instance, subtracting the hybrid motor vehicle portion from the passenger car sector of an IO table would better specify the sector of non-hybrid passenger cars. However, even without the subtraction, the IO data still provide an average of the entire passenger car sector (including hybrids) and does not double count the LCI results (see also Strømman et al. 2009).

Though the subtraction of process data from the IO portion will lead to an improvement in the overall quality of the data, the level of improvement is not critically important. Therefore, this step is optional.

3.6 Integration of BEES and SUTs and calculation of LCIs

Once all the matrices are prepared, they are integrated as described in “Section 2.4”, which completes the data preparation required for the hybrid BEES database. Necessary analytical tables are drawn from these matrices and the LCIs for hybrid BEES are calculated.

3.7 Test run and evaluation of the results (interpretation)

Once the initial LCIs are calculated, they are evaluated in terms of completeness, sensitivity, and consistency. The initial LCIs may need to go through additional rounds of revision as a result of the evaluation. The quality of the hybrid LCIs can be improved through an iterative process of identifying major improvement opportunities and revising the underlying data accordingly.

4 Discussion

In this paper, we discussed the framework under which a hybrid LCI database can be built, using the process for developing hybrid BEES as an example. Transforming existing process-based LCI databases into hybrid LCIs expands the accessibility of the hybrid approach from the small circle of hybrid LCA researchers to lay LCA practitioners. Therefore, the development of hybrid LCI databases is an important step to bringing academic research on the hybrid approach into practice.

Though there are currently a number of initiatives to develop hybrid LCIs, discussion of methodology is still in its infancy. The current paper is expected to provide useful insight for the future development of hybrid LCI databases.

4.1 Recommendations

Based on our study, we have identified a number of recommendations that will help ease future attempts at hybridizing existing process LCI databases. First, data on the price of inputs can substantially improve the quality and the efficiency of the hybridization procedure, yet such data are largely unavailable in existing process LCIs. Providing price information for the inputs and outputs of a unit process would be very helpful for hybridization. Second, clearly documenting the cutoffs would be highly desirable. Significant time and effort are spent on estimating cutoff flows during the hybridization process due to lack of consistent documentation, despite the ISO requirement to report cutoff choices. Third, it would be ideal to design LCI databases with a hybrid approach from the beginning. After an LCI database is constructed, useful information for hybridization gets lost over time, and hybridization becomes more difficult. Even if a project does not intend to create a full hybrid LCI database, it is recommended to consider during the initial construction of the LCI database what data requirements would be needed for hybridization so that useful information can be preserved for later use.

4.2 Limitations

There are limitations to the approach presented. First, we had to prioritize key processes for the estimation of cutoffs due to the sheer number of processes involved and the limited resources and time available. Although we believe that the method of prioritization presented in this paper is based on sound reasoning, some important processes may have been overlooked if they were not identified during the contribution analysis. Second, collection of environmental flow data at the item level has been a challenge, as few public statistics are compiled at that level of detail. Although we have collected environmental flow data from diverse sources, we believe that some of the data are still deficient and need further improvement.

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