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Towards an automated approach for compiling hybrid life cycle inventories

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Abstract

There is an urgent need to reduce the environmental effects associated with the built environment. While a life cycle approach is considered essential for ensuring that these effects are not simply shifted from one life cycle stage to another, not all life cycle assessment methods provide the same level of detail. Three main approaches are currently used to compile a life cycle inventory capturing data on the inputs and outputs associated with a particular good or service: process, input-output and hybrid analysis. While process analysis is recognised for its specificity, it typically involves a truncation of the system boundary. Conversely, input-output analysis is systemically complete, but aggregates data at the economic sector or commodity level. Combining these two methods in a hybrid analysis has the potential to reduce their limitations, while maintaining their benefits. However, combining process and input-output data remains a highly manual and time-consuming process. The development of an automated approach for compiling life cycle inventories is a critical step in the uptake of hybrid analysis methods. This study aims to explore automating the hybridisation of process and input-output data using the Path Exchange method. Major practical barriers that usually prevent automating the integration of process and input-output data in hybrid life cycle inventories are discussed and a case study focusing on concrete is used for the purpose of illustrating the approach.

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Keywords: Life Cycle Assessment; hybrid analysis; construction; automation; industrial ecology virtual laboratory

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1. Introduction

There is an urgent need to reduce environmental effects associated with the built environment. In 2003, the OECD estimated that the building sector accounted for around 25 to 40% of final energy use and 30 to 50% of commodity flows in OECD countries [1]. More recently, the Intergovernmental Panel on Climate Change found that *"the building sector accounted for around 32% of final energy use and 8.8 Gt CO_2 emissions, including direct and indirect emissions"* [2]. The built environment is therefore a significant contributor to global anthropogenic greenhouse gas emissions, and thus to on-going human induced climate change effects. Reducing these effects is paramount, and effective means for measuring these is a critical step in this direction.

Using a life cycle approach is now considered essential in environmental assessments, for ensuring that strategies aimed at mitigating environmental effects are not simply shifting them from one life cycle stage to another. For example, in Australia, the Green Building Council (GBCA) now provides credit in its green building rating scheme for a life cycle assessment (LCA) to be conducted [3]. The LCA method enables a clearer picture of the environmental effects arising at different stages of the life cycle for any given product system – including buildings, the identification of hotspots on which to focus efforts, and an assessment of the benefits of alternative practices.

Three approaches are currently used to compile a life cycle inventory: process analysis, input-output analysis and hybrid analysis. These methods have been described in detail in the literature and the review of their strengths and weaknesses falls outside the scope of this paper. A brief description is provided below, but readers are referred to previous publications for a more detailed overview [inter alia 4, 5-11].

1. **Process analysis** requires the system analysed to be broken down into a series of processes representing the life cycle of the product. It uses specific production process data collected directly from manufacturers or industries. Typically, process analysis relies on the use of background databases managed by specialised institutions such as ecoinvent, who focus on collecting average data for a range of processes [12]. A process analysis is considered specific, and can be used to compare production systems. On the other hand, it suffers from a systematically truncated system boundary, and is therefore likely to underrepresent the total environmental effects analysed.

2. **Input-output analysis (IOA)** is a method based on the use of macroeconomic data collected by national statistics agencies in the form of input-output tables [13, 14]. These tables are combined with sector-based environmental data referred to as satellites (e.g. national energy accounts) to form an environmentally-extended input-output analysis (EEIOA). The systematic manner in which data is collected means that it provides a complete overview of the economy. Every transaction between every sector is recorded. Used for the purpose of LCA, its upstream system boundary is virtually infinite. On the other hand, it suffers from being aggregated at the sector level. Moreover, it relies on prices, which may affect the results in a way that is not representative of reality. This makes it difficult to assess specific products, and impossible to draw comparisons between practices taking place within the same economic sector.

3. **Hybrid analysis** combines process and input-output analysis to address the shortcoming of both methods while retaining their strengths. Four hybridisation techniques have been developed: tiered hybrid [8], path exchange [4, 15], matrix augmentation [9, 16, 17], and integrated hybrid [10].

2. Aim

While the scientific literature is rich in applications of hybrid methods, none have made their way into mainstream applications. The purpose of the project described in this paper is to develop a model to facilitate the application of hybrid methods during the compilation of a life cycle inventory. In particular, the project focuses on the Path Exchange method (PXC), first proposed by Treloar [4], validated by Crawford [18], and formalised by Lenzen and Crawford [15].

The first step of the PXC method is to mathematically disaggregate the input-output (IO) matrix into a series of mutually exclusive nodes, each representing a good or service provided by a particular IO sector. Node to node connections represent a transaction between IO sectors, i.e. the purchase of a good or service from one sector by another. A series of nodes, corresponding to a chain of transactions leading to the sector being assessed, is referred to as a pathway. Specific nodes are then modified using process data that corresponds with the particular transaction. The modifications can affect either the value of the transaction, if identified as different for the particular good or service under study, or the environmental flow associated with the transaction, if specific process data is available.

Disaggregating the IO matrix and working on mutually exclusive nodes is an added benefit of the method. Unlike other hybridisation methods, modifications to the supply chain are performed solely on discrete nodes, and thus do not require other changes within the overall matrix. Applying the PXC method minimises the chance of system boundaries truncation while at the same time reducing the aggregation error as much as possible. Several authors have explored the mathematic formulations underlying the PXC method [4, 7, 15, 19]. Although the PXC method was proposed almost 20 years ago, its application has been limited to a small group of scientists. In the authors' opinion, this is essentially due to the following two issues:

1. **Complexity of the method:** the structural path analysis requires significant computation to disaggregate the input-output matrix and rank transactions. It cannot efficiently be done manually. This was already understood when first proposed, and Treloar [20] developed an algorithm to automate this process. Past this point, practitioners need to identify process data that relates to specific input-output nodes. The aggregated nature of input-output data makes this process particularly difficult, as industrial sectors often cover a large number of products and processes. Identifying what products or processes are covered by a specific transaction between sectors thus requires a reasonable understanding of the product's supply chain. The exchange of input-output data is typically done manually, using relatively simple spreadsheet models. Consequently, a significant level of manual manipulation of data is required.

2. **Absence of available computational tools:** to this date, no software has successfully implemented the PXC method, in an automated or semi-automated manner, or provided an approach to facilitate its implementation. The development of professional LCA software (e.g. Simapro or GaBi) and of high quality process databases (e.g. ecoinvent) has played a crucial role in the uptake of process analysis. The lack of available and recognised tools for the implementation of hybrid analysis is therefore a probable cause for the limited uptake of the method by researchers and practitioners.

The aim of this paper is to address this gap by proposing a conceptual model for automating the Path Exchange method. This will help overcome the first and major limitation preventing the uptake of hybrid analysis. The future implementation of the automated PXC method on the Industrial Ecology Laboratory [21] platform will then address the second limitation by providing the LCA community with a powerful tool for hybrid analysis. The scope of this paper is limited to presenting the proposed model – details of the script are not discussed here. This paper is structured in 6 Sections. Section 3 focuses on the methodology underlying the model, while Section 4 describes a specific case-study to demonstrate the application of the PXC method. Section 5 discusses the usefulness and potential pitfalls associated with the model before concluding in Section 6.

3. Method

This section provides an overview of the path exchange method, before detailing the critical steps involved in its application. Finally, the potential outputs of the automated PXC model are discussed.

3.1. Overview of the Path Exchange method

The model discussed here follows the PXC method as proposed by Treloar [4] and Lenzen and Crawford [15]. As a first step in the model development, the PXC method is broken down into a series of steps for which script can be developed. The result of this work is shown in Fig. 1. The entire process is divided into three sections – process data in orange, input-output data in yellow and product hybridisation in green. First is the collection and formatting of process data (steps A1 to A4), during which one or several process databases are manipulated to be turned into technological matrices, where inputs and outputs from each process in the database are formatted as a matrix. A module developed by Majeau-Bettez [22] is used in this process, and additional script has been developed to extract metadata from a process database's individual datasets in a systematic manner.

The second section involves working on the input-output database that will be hybridised (steps B1 to B3). Here, the most up-to-date matrix of technical coefficients available [13] – or 'A' matrix – is collected from the Industrial Ecology Virtual Laboratory (IELab, http://ielab.info), a collaborative virtual laboratory platform [21]. This is used to calculate a vector of total requirements (TR), using the Leontief inverse [13]. Using the environmental satellites available on the IELab platform, the total environmental flow associated with a dollar of purchase from each sector of the IO matrix is calculated (covering the cradle-to-sale life cycle). The computations are straightforward algebra, and considered standard practice in conducting an EEIOA. The IELab is used as it contains the most up-to-date IO data for Australia and an unprecedented level of disaggregation, with up to 1284 economic sectors represented. Further detail regarding EEIOA is available in [13, 14, 23].

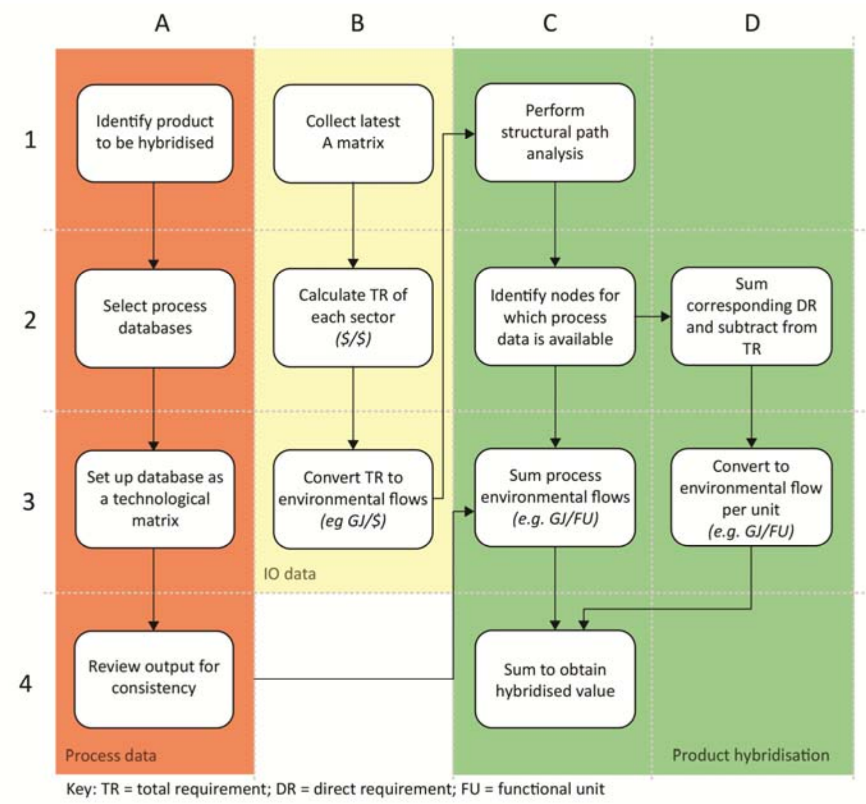

Fig. 1. Hybridisation concept for a single product.

The first two sections (orange and yellow) are relatively straightforward, and will only need to be updated when new process or IO data is published. The third section, the hybridisation process (steps C1 to D4), represents the more complex aspect of the model. It starts by performing a structural path analysis on the sector referring to the product being analysed (step C1). During this step, the matrix is unraveled, to show and rank by level of significance all transactions required for the sector to deliver its output. Applying a threshold value to reduce the number of transactions to a workable amount, the model then assesses each transaction and maps potential equivalent process data (step C2). To do so, it uses available metadata to correlate specific process data to each transaction. The environmental flows associated with these process data are then summed proportionally to the functional unit considered (step C3). The pure IO version of the modified nodes is kept in memory, and the direct requirement associated with each is summed and subtracted from the total requirement of the sector (step D2). The result of this calculation is generally referred to as the 'IO-remainder', and represents the input-output data which is not modified by process data. The value of the IO-remainder, originally in environmental flow per dollar of purchase, is then converted to an environmental flow per functional unit (step D3). Finally, the process data flows and IO-remainder are summed to obtain a hybridised environmental coefficient for the product considered (step C4).

The critical aspects of the hybridisation process are discussed in more detail in the following sub-section.

3.2. Critical steps

Based on a review of the literature on the PXC method [15, 20], the critical steps are to conduct the structural path analysis - or SPA (step C1), and to match individual input-output nodes with process data available in existing databases (step C2). Fig. 2 depicts these steps.

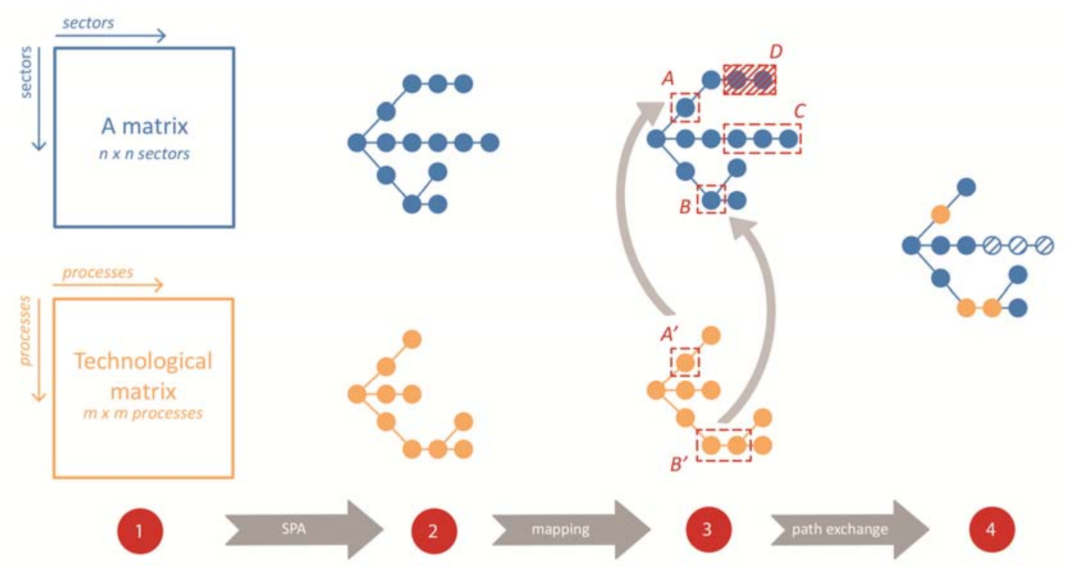

Fig. 2. Conceptualisation of the Path Exchange method.

The SPA is now standard routine in EEIOA, which can be used within the IELab's collaborative platform. An algorithm for conducting the SPA was first made available when the method was discussed by Treloar [4]; an optimized version has since been proposed by Hong, et al. [24]. The key innovation of the proposed model is to develop an automated approach for mapping equivalent input-output and process data. By mapping process and IO data (as shown in Fig. 2), the model will identify sections of the input-output supply chain which can be matched and replaced with sections of the process supply chain. A number of situations are likely to appear and the model needs to have the flexibility to address each of them. The four most likely scenarios (A, B, C and D), as illustrated in Fig. 2, are discussed in further detail in Section 4.

While automating the mapping of process and input-output data is still in progress, the approach used will involve the extensive use of metadata to draw analogies between IO sectors and process data. This will offer the potential for the model to be extended to other input-output matrices and process databases.

The model will use metadata from a number of sources, and will include the possibility to add new sources as they become available. In the case of ecoinvent [25], metadata is extracted from each individual dataset and stored using an algorithm. Ecoinvent uses the United Nation's economic sector classification [26], as well as a text description of the process coverage for each data point. The input-output tables stored on the IELab [27] use a different form of sector classification. However, a series of concordance tables published by the Australian Bureau of Statistics [28, 29], will support the mapping between these two sets of classifications.

The development of the model is likely to draw on recent achievements in the area of artificial intelligence, machine learning, artificial neural networks, etc., which will be explored to assess the potential for a self-training algorithm. At minima, the algorithm will retain information provided by the user in terms of the choices that are made in exchanging IO data for a specific node with process data. This will help speed the process up, and will help increase the accuracy of the assessment over time.

A complete automation of this mapping and matching process may be difficult to achieve, as a certain level of expert judgement might be required to verify that the matches suggested by the algorithm are accurate. Several approaches will be explored in attempting to resolve this issue. First, an algorithm relying on matching sector classifications between input-output tables and process databases, as well as extracting keywords from the metadata will be created. It is envisaged that the output of this analysis will be a list of up to 10 different process datasets drawn from the available databases. The user will then be allowed to choose one, or several of these processes, to replace the IO data for a given node. To increase the efficiency of this process, the algorithm will focus on nodes exceeding a threshold value defined by the user.

Using this approach will help facilitate the mapping and identification of equivalent process and input-output data, in order to make the hybridisation process as a whole less labour intensive and more efficient.

3.3. Output

Several outputs may be drawn from the assessment, besides hybrid coefficients. Graphic interpretations of the results will be provided. This will include, for example, a representation of the supply chain as a process tree, including a depiction of sections of the tree that are represented by process and/or input-output data. It would also be possible to superimpose the graphic representation of the supply chain as shown by process and input-output data, and their hybrid versions.

The model will also be able to report on the total proportion covered by process and input-output data, and compare the total intensity with these obtained with pure process and input-output datasets.

The Path Exchange method is used in an effort to tailor the input-output supply chain to a specific output, thus increasing the specificity of the results while retaining a complete system boundary. The model developed as part of this project will aim to complete this task efficiently, in an automated or semi-automated manner. The case-study described in the following section illustrates some of the key aspects of the model.

4. Illustration of the PXC method using an existing case study

In this section a case study from the recent literature is used to illustrate the critical steps of the hybridisation process. This case study, used by Crawford [7], focuses on the embodied energy requirements for the production of concrete, a material used on the majority of construction sites. Crawford [7] used a more aggregated version of the Australian input-output tables (106 sectors). As the proposed model will be able to access a much more disaggregated version of the input-output tables for Australia (1284 sectors), the output of the original assessment has been modified to be in line with the most recent sector nomenclature.

Table 1. Top ten nodes for energy flows in the ready mixed concrete and mortar sector (adapted from [7]).

	Node, by sector name
1	Direct (*i.e.* direct energy requirement of the *'Ready mixed concrete and mortar'* sector)
2	Margin road freight and transport services
3	Cement
4	Aggregate
5	Margin road freight and transport services > Margin road freight and transport services
6	Margin road freight and transport services > Cement
7	Margin road freight and transport services > Gravel
8	Cement > Cement
9	Margin – railway freight transport services
10	Limestone

Note: the names of the sectors were modified to be in line with the 1284 sectors used in IELab.

The first step in the hybridisation process (step C1 of Fig. 1) is to run the structural path analysis (SPA) on the IO sector relating to concrete production, in this case the *'Ready mixed concrete and mortar'* sector. The output of this process is a list of thousands of individual nodes, each representing a single good or service and its associated direct energy requirements (DER). The sum of IO DER for all of these nodes equals the total energy requirement of the sector to produce one dollar of output. The ten most significant nodes are shown in Table 1. Node 3 ('cement') represents inputs from direct suppliers from the cement industry whereas Node 8 ('cement > cement') represents second tier suppliers, i.e. other companies from the cement industry that supply to the direct suppliers.

The system boundary diagram in Fig. 3 is adapted from Sharma and Grant [30]. It reports the processes modelled during the process analysis of concrete production, themselves interlinked with the background database (here, the Australian Life Cycle Inventory database AusLCI). Using the technology and A matrices, our algorithm will be capable of producing similar diagrams to mimic a pure process and input-output analysis. It will, for instance, show the relative importance of the different steps in the process tree by reporting the direct environmental flows associated with their inputs. This type of analysis will be particularly useful to the user when selecting the nodes proposed by the algorithm.

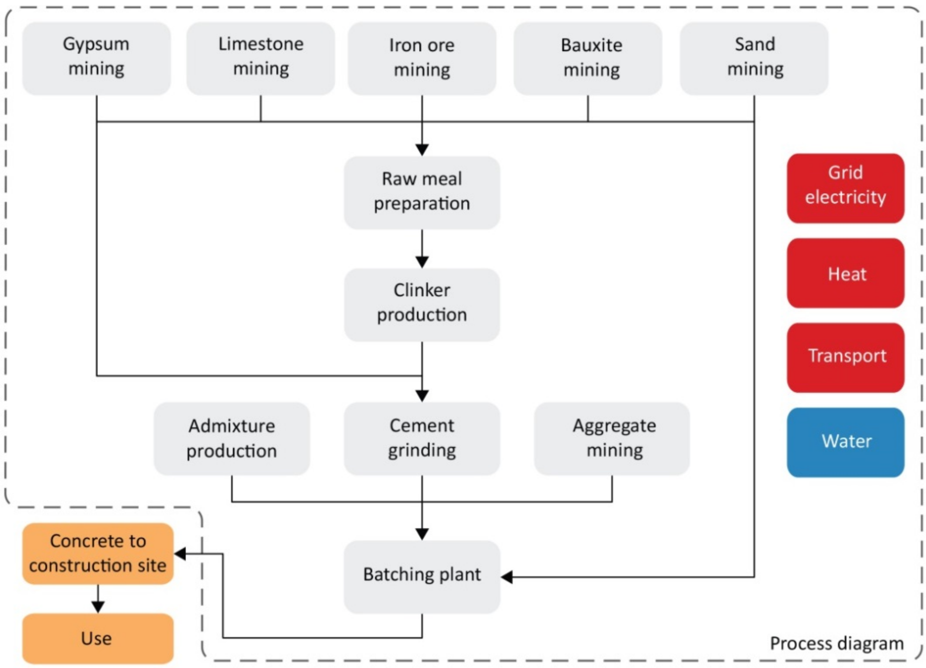

Fig. 3. Concrete production process diagram (adapted from [30]).

The model will inevitably face a variety of scenarios when mapping and matching process data with IO nodes; it will need to have the flexibility to address each one individually. Fig. 2 illustrates the type of scenarios expected; each one is discussed in further detail below.

A. The simplest scenario is for a node to directly match with a single process data point (A → A' in Fig. 2). An example from the case study would be the *'Gravel'* sector input into the *'Ready mixed concrete and mortar'*, which could be substituted with the *'Aggregate mining'* process in Fig. 3.

B. Given the aggregated nature of input-output data, a likely scenario is for several individual process data points to cover a single node (B → B' in Fig. 2). In the case study, this can be illustrated by the *'Cement'* sector input, which covers several process data points including those representing *'raw meal preparation'*, *'clinker production'* and *'cement grinding'*.

C. The third probable scenario is the absence of process data matching potentially significant nodes (C in Fig. 2). In this case, the model will allow the user to enter specific values from other sources when available, alongside metadata on the source to be collated for future reference. This is for instance the case of node 16 (not shown on Table 1), which refers to a transaction from the *'Non-margin – wholesaling services'* sector. There is very little to no available process data for services in most process databases. If these were to become available from a different source, it will be possible to modify the associated node manually.

D. The fourth scenario relates to sections of the supply chain which may be irrelevant for the product being assessed (D in Fig. 2). As economic sectors often cover a range of goods and services, some inputs might not be relevant to the product assessed and should therefore be subtracted from the final output.

Apart from these broad scenarios, the model will allow the user to modify an intensity (*i.e.* the 'quantity' being purchased), and/or a node coefficient (*i.e.* the environmental flow associated with the transaction). As mentioned earlier, the most innovative aspect of the model will be to automate this process, whilst allowing for semi-automated or entirely manual modifications.

It is probable that in most cases, the replacement of IO data with process data will focus on the node coefficient, as it will use specific values that are more representative of the product being assessed. The modification of intensities will be less common, but will be particularly useful for inputs such as freight. More accurate data based on distance between production sites may be available, and would take into account the local characteristics of a supply chain.

Finally, the model will also enable the modification of a proportion of a node. By default, the modifications done on a node affects it as a whole. It is possible however that the user will want to modify only a specific proportion of a node. This cannot be illustrated with the case study discussed here, however the work undertaken by Baboulet and Lenzen [19] provides examples and justifications for modifying a fraction of a node.

5. Discussion

5.1. Potential applications

This model is still in the early stages of development. Once completed, it will help accelerate the generation of comprehensive hybrid data, and will provide a level playing field for the use of the Path Exchange method by the wider LCA community. Preferred hybrid methods of assessment keep the IO 'top-down' approach, starting at the sector level and improving specificity as process data are added. Once applied to the assessment of the built environment, the model will help provide more comprehensive assessments of building materials and components as well as whole buildings. Previous work has shown that using the Path Exchange method in the assessment of buildings results in a more comprehensive appraisal of the building's embodied environmental effects [31, 32]. This, in turn, will lead to more appropriate and targeted mitigation practices, focusing on broader life cycle environmental effects, as opposed to the current practice which tends to focus on operational effects alone.

Additionally, working towards an automated model is an important step for the further development of hybrid analysis. It will provide a common platform for testing and discussing the Path Exchange method's benefits and shortcomings relative to other methods of assessment. The work done to develop this model could also be used as the foundation for automating other hybrid methods, for instance the Integrated Hybrid method proposed by Suh and Huppes [10].

5.2. Potential pitfalls

Matching IO data with process data requires that several aspects are taken into account. For instance, the level of aggregation of the input-output table will play a crucial role in the degree of difficulty in drawing analogies between these two types of data. Here, the model relies on input-output data from the IELab with the highest sector resolution in the realm of input-output analysis (1284 sectors are represented).

In addition, process databases such as ecoinvent are often built with considerations for input-output analysis and include a sectorial classification of all processes. Although this classification is different from the one used by the IELab, it is built following a relatively similar structure, thus an efficient concordance table may be built to link the two sets of classifications. Additionally, the amount of metadata provided with each dataset is significant. Using a solid semantics analysis method, it should be feasible to draw enough information to complete the matching.

Process databases are not necessarily built with a structure that is as standardised as input-output tables. For instance, some process data points are used to aggregate several other process datasets into one. An algorithm may consider this as a multitude of processes feeding into one when in fact it is a way to create a weighted average – something found routinely in process databases to produce a data point representative of average practices. Rules will need to be implemented to avoid using these datasets. Additionally, the structure of a database may change from one version to another, meaning that the model would need to be reviewed when new versions of a database are published.

Finally, there is an inherent risk associated with relying on an algorithm and/or artificial intelligence to solve complex problems. Even using the most up-to-date artificial intelligence technology, it is probable that the model will not be able to complete its task without any human input. For this reason, a semi-automated model is an envisaged solution for providing suggestions of path exchange rather than a completely automatic implementation. To reduce risks associated with the use of an algorithm, its development will follow the guidelines laid out by Pauliuk, et al. [33] on software development and openness, and the general computing guidelines they refer to. Using these guidelines will provide support in producing a high quality model, which can be used by other scientists, and collaboratively modified and improved upon.

5.3. Limitations

The Path Exchange method includes a high level of uncertainty associated with interpreting the correspondence between a transaction from a sector to another and a physical process. Furthermore, the aggregated nature of input-output tables means that a transaction from a sector to another represents in fact a significant number of transactions between various businesses. As such, it is an oversimplification to assume that a node would refer to a single production process or business.

These limitations need to be taken into account when analysing results, and especially when comparing products. No assessment method will show with complete accuracy the flows associated with any given process, material or product. Each method rests on a set of assumptions, and is able to shed only some light on an aspect of the process, material or product being assessed. Uncertainties and margins of error are something that always needs to be taken into account in LCAs, and the proposed model will consider this.

6. Conclusion

Hybrid methods for compiling life cycle inventories are used to combine the strengths of process and input-output methods while addressing their major shortcomings. Although a variety of methods have been proposed over the past four decades, none have yet been implemented for mainstream application. One reason for this is the complexity associated with hybrid analysis and the time consuming nature of hybrid methods for compiling life cycle inventories. This study provides a conceptual framework for automating the hybridisation of process and input-output data, streamlining the existing manual approach and overcoming one of the main barriers to the uptake of hybrid analysis. This in turn will enable practitioners to comprehensively assess environmental effects associated with the built environment, and, ultimately, reduce them.

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