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LCA Methodologies
an Annotated Bibliography

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1 Introduction

Life-Cycle Assessment (LCA), also known as *Life-Cycle Analysis*, and *Cradle-to-Grave Analysis*, is a technique to investigate, estimate, and evaluate the environmental impacts caused by a material, product, process, or service throughout its life span. Environmental impacts include the raw materials and energy resources required to produce the products, as well as the wastes and emissions generated during the process. LCA could provide a complete picture of the environment impacts created from one period of the life cycle to another, which helps to identify which impacts are the most significant across the life cycle. Its applications include government policy, strategic planning, marketing, consumer education, process improvement and product design. There are three methodological variants of LCA: ***Process-based LCA, Economic Input-output LCA, and Hybrid LCA***.

This annotated bibliography is a work in progress to collect and organize studies of LCA methodologies. The literature contained the representative articles for each methdologies. The abstracts of the articles are included if available (*Users should refer to the original published articles for the full abstract.*) This bibliography is expected to continue to update.

* American National Standard, 1997. Environmental Management Life Cycle Assessment - Principles and Framework. ANSI/ISO 14040 - 1997. `http://www.ce.cmu.edu/~hsm/lca2007/readings/iso14040.pdf`

* Bilec M., Ries R., Matthews H.S., Sharrard A.L., 2006. Example of a Hybrid Life-Cycle Assessment of Construction Processes.*Journal of Infrastructure Systems*. 12(4), 207-215.

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2 Process-based LCA Method (PLCA)

The initial approach to completing a LCA is a process-based LCA method, which calculates the amount of commodities required to produce a certain functional unit. PLCA method evaluates the raw materials and energy resources flow for each process within the system life cycle. It has often been employed to evaluate the direct and indirect environmental impacts associated with specific production processes. However, this method relies on actual data for each step, and requires defining a system boundary for analysis. Therefore, it suffers the limitation of systematic errors due to the unavoidable truncation of the system boundary.

* Bayart J.B., Bulle C., Deschenes L., Margni M., Pfister S., Vince F., Loehler A., 2010. A Framework for assessing off-stream freshwater use in LCA. *The International Journal of Life Cycle Assessment*. 15, 439-453.

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* Zapata P., Gambatese J.A., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction.*Journal of Infrastructure Systems.* 11(1), 9-20.

3 Economic Input-Output based LCA Method (EIO-LCA)

Economic input-output based LCA method is the combination of the LCA analysis and economic input-output analysis. LCA is a bottom-up approach based on individual processes, while input-output analysis is a top-down approach, which originally developed by Leontief (1936) describes how monetary transaction flows between economic sectors. The advantage of EIO-LCA method is the completeness of system boundaries since the entire economic activities of a nation state or the global economy are represented. Despite the comprehensive framework and complete data analysis, EIO-LCA method is subject to many uncertainties, due mainly to the high level of aggregation of products.

* Green Design Institute, Carnegie Mellon University. Economic Input-Output Life Cycle Assessment. `http://www.eiolca.net/`

- * Hendrickson C., Horvath A., Joshi S., Lave L., 1998. Economic Input-Output Models for Environmental Life-Cycle Assessment. *Environmental and Policy Analysis.* 32(7), 184-191.
- * Lave L.B., Cobas-Flores E., Hendrickson C.T., McMichael F.C., 1995. Using I-O analysis to estimate economy-wide discharges. *Environmental Science and Technology.* 29(9), 420-426.
- * Ochoa L., Hendrickson C., Matthews H.S., 2002. Economic input-output life-cycle assessment of U.S. residential buildings. *Journal of Infrastructure Systems.* 8(4), 132-138.
- * Suh S., Huppes G., 2002. Missing inventory estimation tool using extended input-output analysis. *The International Journal of Life Cycle Assessment.* 7(3), 134-140.

4 Hybrid LCA Method (HLCA)

4.1 Process-based hybrid LCA method

Process-based hybrid LCA method defines the inputs into the main processes in terms of physical units. By substituting the monetary values of the I/O table with the physical units, the reliability and accuracy of the I/O method will be highly increased. Therefore, the main disadvantage of I/O analysis (aggregation and proportionality of monetary values of sectors) can be compensated with this method.

- * Heijungs R., 1994. A generic method for the identification of options for cleaner products. *Ecological Economics.* 10, 69-81.
- * Heijungs R., Suh S., 2002. The computational structure of life cycle assessment. Dordrecht, The Netherlands Kluwer Academic Publisher.
- * Lenzen M., 2001. Error in conventional and input-output based life cycle inventories. *Journal of Industrial Ecology.* 4(4), 127-148.
- * Treloar G.J., 1998. A comprehensive embodied energy analysis framework. Ph.D. Thesis. Deakin University, Geelong.

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4.2 Input-output based hybrid LCA method

Input-output based hybrid LCA method uses conventional I/O analysis data as the starting point. Sector data in the I/O table are substituted with process analysis data. However, substituting process data may cause unwanted flow-on effects, which are likely to worsen the proportionality assumption problems of the I/O modelling.

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* Treloar G.J., Love P.E.D., Holt G.D., 2001. Using national input-output data for embodied energy analysis of individual residential buildings. *Construction Management and Economics*. 19, 49-61.

4.3 Tiered hybrid LCA method

Tiered hybrid LCA method exploits the strength of both PLCA and EIO-LCA. Process analysis is used for the upstream processes, such as use and disposal phases, and the remaining input data are taken from I/O analysis. The disadvantages of this method are double counting, and the interaction between the two methods can be difficult to assess in a systematic way.

* Bullard C.W., Penner P.S., Pilati D.A., 1978. Net energy analysis: handbook for combining process and input-output analysis. *Resource and Energy*. 3, 267-313.

* Hondo H., 2005. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy*. 30, 2042-2056.

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* Moriguchi Y., Kondo Y., Shimizu H., 1993. Analyzing the life cycle impacts of cars: the case of CO_2. *Industry and Environment*. 16(1-2), 42-45.

* Munksgaard J., Wier M., Lenzen M., Dey C., 2005. Using input-output analysis to measure the environmental pressure of consumption at different spatial levels. *Journal of Industrial Ecology*. 9(1-2), 169-185.

* Stromman A.H., Peters G.P., Hertwich E.G., 2009. Approaches to correct for double counting in tiered hybrid life cycle inventories. *Journal of Cleaner Production*. 17, 248-254.

4.4 Integrated hybrid LCA method

Integrated hybrid LCA method integrates the bottom-up process analysis into a top-down I/O analysis. In this method, process analysis and I/O analysis are developed independently and then systematically merged into one system, which could model the full interactions between individual processes and industries in a coherent way. However, this method requires high data and time.

* Acquaye A.A., Wiedmann T., Feng K., Crawford R.H., Barrett J., Kuylenstierna J., Duffy A.P., Koh L., McQueen-Mason S., 2011. Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis. *Environmental Science and Technology.* 45, 2471-2478.

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* Wiedmann T.O., Suh S., Feng K., Lenzen M., Acquaye A., Scott K., Barrett J.R., 2011. Application of hybrid life cycle approaches to emerging energy technologies – the case of wind power in the UK. *Environmental Science and Technology.* 45, 5900-5907.

5 Alphabetical Listing of Sources and Abstracts

Bayart J.B., Bulle C., Deschenes L., Margni M., Pfister S., Vince F., Loehler A., 2010. A Framework for assessing off-stream freshwater use in LCA. *The International Journal of Life Cycle Assessment.* 15, 439-453.

Freshwater scarcity is a problem in many areas of the world and will become one of the most sensitive environmental issues in coming decades. Existing life cycle assessment (LCA) methodologies generally do not provide assessment schemes or characterization factors of the potential environmental impacts of freshwater use or freshwater resource depletion. These assessments therefore do not account for the significant environmental consequences of the loss in quality and availability of freshwater. This paper aims to develop a framework to address this methodological limitation and to support further quantitative modeling of the cause–effect chain relationships of water use. The framework includes recommendations for life cycle inventory (LCI) modeling and provides a description of possible impact pathways for life cycle impact assessment (LCIA), including indicators on midpoint and endpoint levels that reflect different areas of protection (AoP). The framework provides recommendations for the development of operational LCA methods for water use. It establishes the link between LCI and LCIA, water use mechanism models, and impact pathways to environmental damages in a consistent way.

Bilec M., Ries R., Matthews H.S., Sharrard A.L., 2006. Example of a Hybrid Life-Cycle Assessment of Construction Processes. *Journal of Infrastructure Systems*. 12(4), 207-215.

Design and construction industries, along with owners, have an increasing interest in and responsibility for the environmental impacts of buildings. Since the environmental impacts of a building's life cycle are considerable, quantification of all phases is important, especially the construction phase, which is often glossed over. This research focuses on the construction phase of a building project. Generally, the life-cycle inventory created in performing a life-cycle assessment(LCA) is developed using either a process or input–output approach; however, both techniques have distinct advantages and disadvantages. A hybrid approach combining both methods' advantages has been proposed and will be demonstrated. Existing hybrid models are reviewed, along with a recommendation of a hybrid model for construction. A preliminary case study of a precast concrete parking garage's construction using hybrid LCA methodology is presented. Preliminary investigations indicate transportation, equipment activity, and support functions have the largest effects on the environment.

Borjesson P., Gustavsson L., 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives.*Energy Policy*. 28, 575-588.

In this paper, primary energy use and carbon dioxide (CO_2) and methane (CH_4) emissions from the construction of a multi-store building, with either a wood or a concrete frame, were calculated from life-cycle and forest land-use perspectives. The primary energy input (mainly fossil fuels) in the production of building materials was found to be about 60-80 percent higher when concrete frames were considered instead of wood frames. The net greenhouse gas (GHG) balance for wood materials will depend strongly on how the wood is handled after demolition of the building. The net GHG balance will be slightly positive if all the demolition wood is used to replace fossil fuels, slightly negative if part of the demolition wood is re-used, and clearly positive if all wood is deposited in landfills, due to the production of CH_4. However, if the biogas produced is collected and used to replace fossil fuels, the net GHG emissions will be insignificant. If concrete frames are used, the net GHG emissions will be about those when demolition

wood from the wood-framed building is deposited in landfills and no biogas is collected. We have considered that the CO_2 released from the chemical processes in the production of cement will be re-bound to the concrete by the carbonization process. Otherwise, the net GHG emission would be more than twice as high when concrete frames are used. If forest biomass is used instead of fossil fuels, the net area of forestland required to supply both raw material and energy for the production of building materials, will be about twice as high when wood frames are used instead of concrete frames. However, the GHG mitigation efficiency, expressed as CO_2 equivalents per unit area of forest land, will be 2-3 times higher when wood frames are used if excess wood waste and logging residues are used to replace fossil fuels. The excess forest in the concrete frame alternative is used to replace fossil fuels, but if this forest is used for carbon storage, the mitigation efficiency will be higher for the first forest rotation period (100 yr), but lower for the following rotation periods. Some of the data used in the analyses are uncertain, but an understanding of the complexity in comparing different alternatives for utilizing forest for GHG mitigation, and of the fact that the time perspective applied affects the results markedly, is more important for the results than the precise figures in the input data.

Bullard C.W., Penner P.S., Pilati D.A., 1978. Net energy analysis: handbook for combining process and input-output analysis. *Resource and Energy.* 3, 267-313.

Methods are presented for calculating the energy required, directly and indirectly, to produce all types of goods and services. Procedures for combining process analysis with input-output analysis are described. This enables the analyst to focus data acquisition effects cost-effectively, and to achieve down to some minimum degree a specified accuracy in the results. The report presents sample calculations and provides the tables and charts needed to assess total energy requirements of any technology, including those for producing or conserving energy.

Carpentieri M., Corti A., Lombardi L., 2005. Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO_2 removal. *Energy Conversion and Management.* 46, 1790-1808.

Based on the results of previous studies, the efficiency of a Brayton/Hirn com-

bined cycle fuelled with a clean syngas produced by means of biomass gasification and equipped with CO_2 removal by chemical absorption reached %33.94, considering also the separate CO_2 compression process. The specific CO_2 emission of the power plant was 178kg/MWh. In comparison with values previously found for an integrated coal gasification combined cycle (ICGCC) with upstream CO_2 chemical absorption %38–39 efficiency, 130kg/MWh specific CO_2 emissions), this configuration seems to be attractive because of the possibility of operating with a simplified scheme and because of the possibility of using biomass in a more efficient way with respect to conventional systems. In this paper, a life cycle assessment (LCA) was conducted with presenting the results on the basis of the Eco-Indicator 95 impact assessment methodology. Further, a comparison with the results previously obtained for the LCA of the ICGCC was performed in order to highlight the environmental impact of biomass production with fossil fuels utilization. The LCA shows the important environmental advantages of biomass utilization in terms of reduction of both greenhouse gas emissions and natural resource depletion; although an improved impact assessment methodology may better highlight the advantages due to the biomass utilization.

Crawford R.H., 2004. Using input-output data in life-cycle inventory analysis. Ph.D. Thesis, Deakin University, Geelong.

The impacts on the environment from human activities are of increasing concern. The need to consider the reduction in energy consumption is of particular interest, especially in the construction and operation of buildings, which accounts for between %30 and %40 of Australia's national energy consumption. Much past and more recent emphasis has been placed on methods for reducing the energy consumed in the operation of buildings. With the energy embodied in these buildings having been shown to account for an equally large proportion of a building's life cycle energy consumption, there is a need to look at ways of reducing the embodied energy of buildings and related products. Life cycle assessment (LCA) is considered to be the most appropriate tool for assessing the life cycle energy consumption of buildings and their products. The life cycle inventory analysis (LCIA) step of a LCA, where an inventory of material and energy inputs is gathered, may currently suffer from several limitations, mainly concerned with the use of incomplete and unreliable data sources and

LCIA methods. These traditional methods of LCIA include process-based and input-output based LCIA. Process-based LCIA uses process specific data, whilst input-output based LCIA uses data produced from an analysis of the flow of goods and services between sectors of the Australian economy, also known as input-output data. With the incompleteness and unreliability of these two respective methods in mind, hybrid LCIA methods have been developed to minimize the errors associated with traditional LCIA methods, combining both process and input-output data. Hybrid LCIA methods based on process data have shown to be incomplete. Hybrid LCIA methods based on input-output data involve substituting available process data into the input-output model minimizing the errors associated with process-based hybrid LCIA methods. However, until now, this LCIA method had not been tested for its level of completeness and reliability. The aim of this study was to assess the reliability and completeness of hybrid life cycle inventory analysis, as applied to the Australian construction industry.

Crawford R.H., 2008. Validation of a hybrid life-cycle inventory analysis method. *Journal of Environmental Management.* 88, 496-506.

The life-cycle inventory analysis step of a life-cycle assessment (LCA) may currently suffer from several limitations, mainly concerned with the use of incomplete and unreliable data sources and methods of assessment. Many past LCA studies have used traditional inventory analysis methods, namely process analysis and input–output analysis. More recently, hybrid inventory analysis methods have been developed, combining these two traditional methods in an attempt to minimize their limitations. In light of recent improvements, these hybrid methods need to be compared and validated, as these too have been considered to have several limitations. This paper evaluates a recently developed hybrid inventory analysis method which aims to improve the limitations of previous methods. It was found that the truncation associated with process analysis can be up to %87, reflecting the considerable shortcomings in the quantity of process data currently available. Capital inputs were found to account for up to %22 of the total inputs to a particular product. These findings suggest that current best-practice methods are sufficiently accurate for most typical applications, but this is heavily dependent upon data quality and availability. The use of input–output data assists in improving the system boundary completeness of *life-cycle inventories. However, the use of input–output analysis alone does not always provide an accurate model for replacing process data. Further improvements in the quantity of process data currently available are needed to increase the reliability of life-cycle inventories.*

Crawford R.H., Treloar, G.J., Ilozor, B.D., Love, P.E.D., 2003. Comparative greenhouse emissions analysis of domestic solar hot water systems. *Building Research and Information.* 31 (1), 34-47.

It is commonly assumed that solar hot water systems save energy and reduce greenhouse emissions relative to conventional fossil fuel-powered systems. Very rarely has the life-cycle greenhouse emissions (including the embodied greenhouse emissions of manufacture) of solar hot water systems been analyzed. The extent to which solar hot water systems can reduce emissions compared with conventional systems can be shown through a comparative life-cycle greenhouse emissions analysis. This method determined the time it takes for these net greenhouse emissions savings to occur, or the 'emissions payback period'. This paper presents the results of a life-cycle greenhouse emissions analysis of solar hot water systems in comparison with conventional hot water systems for a southern (Melbourne) and a northern (Brisbane) Australian city. The life-cycle costs of these hot water systems were also analyzed to determine the financial payback period. The fuel source and solar fraction determined the emissions resulting from the energy used for operating hot water systems. The solar systems provide net emissions savings compared with the conventional systems after 2.5–5 years in Melbourne and after 2.5 years in Brisbane, depending on the auxiliary fuel. The life-cycle cost analysis also revealed that the financial payback period for solar hot water systems is more than 10 years in Melbourne and around 10 years for an electric-boosted system in Brisbane. This suggests the need for greater subsidies to increase market take-up for solar systems, especially where electricity is the only available fuel.

Crawford R.H., Treloar, G.J., Fuller, R.J., Bazilian, M., 2006. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. *Renewable and Sustainable Energy Reviews.* 10 (6), 559-575.

Building integrated photovoltaic (BiPV) systems generate electricity, but also

heat, which is typically wasted and also reduces the efficiency of generation. A heat recovery unit can be combined with a BiPV system to take advantage of this waste heat, thus providing cogeneration. Two different photovoltaic (PV) cell types were combined with a heat recovery unit and analysed in terms of their life-cycle energy consumption to determine the energy payback period. A net energy analysis of these PV systems has previously been performed, but recent improvements in the data used for this study allow for a more comprehensive assessment of the combined energy used throughout the entire life-cycle of these systems to be performed. Energy payback periods between 4 and 16.5 years were found, depending on the BiPV system. The energy embodied in PV systems is significant, emphasised here due to the innovative use of national average input–output (I–O) data to fill gaps in traditional life-cycle inventories, i.e. hybrid analysis. These findings provide an insight into the net energy savings that are possible with a well-designed and managed BiPV system.

Ercan T., Tatari O., 2015. A hybrid life cycle assessment of public transportation buses with alternative fuel options. *The International Journal of Life Cycle Assessment.* (20), 1213-1231.

Alternative fuel options are gaining popularity in the vehicle market. Adopting alternative fuel options for public transportation compared to passenger vehicles contributes exponentially to reductions in transportation-related environmental impacts. Therefore, this study aims to present total air pollutant emissions and water withdrawal impacts through the lifetime of a transit bus with different fuel options. As an addition of current literature, LCA of alternative fuel options was performed in this paper for transit buses with the consideration of a wide variety of environmental indicators. Although the results indicate that BE and hybrid-powered buses have less environmental emissions, the US's dependency on fossil fuel for electricity generation continues to yield significant lifetime impacts on BE transit bus operation. With respect to water withdrawal impacts, we believe that the adoption of BE transit buses will be faster and more environmentally feasible for some NREC regions than for others.

Feng K., Hubacek K., Siu Y.L., Li X., 2014. The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis. *Renewable and*

Sustainable Energy Reviews. 39, 342-355.

Between 2000 and 2010, China's electricity production had increased three-fold and accounted for %50 of domestic and %12 of global CO_2 emissions in 2010.Substantial changes in the electricity fuel mix are urgently required to meet China's carbon intensity target of reducing CO_2 emissions by %(40–45) by 2020. Moreover, electricity production is the second largest consumer of water in China, but water requirements vary significantly between different electricity generation technologies. By integrating process-based life-cycle analysis (LCA) and input–output analysis (IOA) and through tracking national supply chains, we have provided a detailed account of total life-cycle carbon emissions(g/kWh) and water consumption(l/kWh) for eight electricity generation technologies – (pulverized) coal, gas, oil, hydro, nuclear, wind, solar photovoltaic, and biomass. We have demonstrated that a shift to low carbon renewable electricity generation technologies, i.e. wind, could potentially save more than %79 of total life-cycle CO_2 emissions and more than %50 water consumption per kWh electricity generation compared to the current fuel mix and technology for electricity generation. If the projected wind farms are built by 2020, Inner Mongolia, one of the water scarce northern provinces, would annually save 179MT CO_2 (i.e. %44 of Inner Mongolia's total CO_2 emissions in 2008) and 418 million m3 (Mm3) water (%18 of its industrial water use in 2008) compared with the same amount of electricity produced from coal.

Finnveden G., Hauschild M.Z., Ekvall T., Guinee J., Heijungs R., Hellweg S., Koehler A., Pennington D., Suh S., 2009. Recent development in life cycle assessment. *Journal of Environmental Management.* 91, 1-21.

Life Cycle Assessment is a tool to assess the environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management. The methodological development in LCA has been strong, and LCA is broadly applied in practice. The aim of this paper is to provide a review of recent developments of LCA methods. The focus is on some areas where there has been an intense methodological development during the last years. We also highlight some of the emerging issues. In relation to the Goal and Scope definition, we especially discuss the distinction between attributional and consequential LCA. For the Inven-

tory Analysis, this distinction is relevant when discussing system boundaries, data collection, and allocation. Also highlighted are developments concerning databases, Input–Output, and hybrid LCA. In the sections on Life Cycle Impact Assessment, we discuss the characteristics of the modelling as well as some recent developments for specific impact categories and weighting. In relation to the Interpretation, the focus is on uncertainty analysis. Finally, we discuss recent developments in relation to some of the strengths and weaknesses of LCA.

Heijungs R., 1994. A generic method for the identification of options for cleaner products. *Ecological Economics.* 10, 69-81.

Life cycle assessment, a method for the assessment of the environmental impacts of products, is briefly explained. A mathematical method to perform the calculations and to identify dominant aspects in the environmental load of a product is developed. The results are used to derive expressions for a marginal analysis which can be used for improvement analysis. In this way, a designer or process engineer can determine which processes or materials to consider first when (re)designing a product. The method developed can also be used to estimate the reliability of the determination of the environmental load of the products analyzed in terms of the reliability of the data of the processes involved.

Heijungs R., Koning A., Suh S., Huppes G., 2006. Toward an information tool for integrated product policy: requirements for data and computation. *Journal of Industrial Ecology.* 10(3), 147-158.

Integrated product policy, according to the European Union, requires reliable data on the impact of consumer products along their life cycles. We argue that this necessarily requires the development of an information tool for hybrid analysis, combining aspects of life-cycle assessment and input-output analysis. A number of requirements in the development of such a hybrid information tool are identified, mainly concerning data and computational structure. For the former, some important points of attention are discussed, whereas for the latter, operational formulas are developed.

Heijungs R., Suh S., 2002. The computational structure of life cycle assessment.

Dordrecht, The Netherlands: Kluwer Academic Publisher.

This book presents a complete overview of the computational aspects of life cycle assessment (LCA). Many books and articles have been written on LCA, including theoretical treatments of the entire concept, practical guidebooks to apply the technique, and concrete case studies in which LCA is applied to support decision-making with respect to environmental aspects of product alternatives. However, a good discussion of the computational structure of LCA is lacking. Knowledge is only partially documented, and what is documented is fragmented over diverse publications with mutual inconsistencies in approach, terminology and notation. The book is the result of several years of research, along with the teaching of LCA at university classes and, not unimportantly, the development of software for LCA. This software has been designed to support the education of LCA, but it has been applied in real-world case studies as well. The name of the software is CMLCA, which is an abbreviation of Chain Management by Life Cycle Assessment. This program can easily be used to reanalyze and further explore the ideas that are outlined in this book. Another important source for this book relates to the work involved in connecting input-output analysis (IOA) to LCA. Software for this – MIET, an abbreviation of Missing Inventory Estimation Tool – is also available. Some of the basic routines have been implemented in Matlab script as well. All three pieces of software can be accessed, free of charge, through `http://www.leidenuniv.nl/cml/ssp/software.html`.

Hendrickson C., Horvath A., Joshi S., Lave L., 1998. Economic Input-Output Models for Environmental Life-Cycle Assessment. *Environmental and Policy Analysis.* 32(7), 184-191.

Process and product models are commonly used for performing life-cycle assessments (LCAs) of the environmental impacts of materials and products through different stages of fabrication, use, and end-of-life options. In this article, we show that these models can be represented as process flow diagrams or as matrices of process interactions. In either representation, the inventory of environmental emissions and resources used is comparable, provided the process models are proportional in nature (any increase in product output produces a corresponding environmental burden). Matrix representations are advantageous if application cost, feedback flow, or speed of analysis is important. They are also

useful in conjunction with comprehensive, general equilibrium models in which the system boundary of the problem (e.g., an LCA of a product) being analyzed is on the level of the national economy.

Henriksson P.J.G., Zhang W.B., Guinee J.B., 2015. Updated unit process data for coal-based energy in China including parameters for overall dispersions. *International Journal of Life Cycle Assessment.* 20, 185-195.

Chinese coal power generation is part of the life cycle of most products and the largest single source for many emissions. Reducing these emissions has been a priority for the Chinese government over the last decade, with improvements made by replacing older power plants, improving thermal efficiency and installing air pollution control devices. In the present research, we aim to acknowledge these improvements and present updated unit process data for Chinese coal power. In the course of doing so, we also explore the implementation and interpretation of overall dispersions related to a generically averaged process, such as Chinese coal power. The present manuscript provides recommendations on how to implement and interpret dispersions propagated into LCI results. In addition, updated and easily accessible unit process data for coal power plants averaged across China and for individual provinces are presented, with clear distinctions of inherent uncertainties, spread (variance) and unrepresentativeness. Recommendations are also provided for future research and software developments.

Hondo H., 2005. Life cycle GHG emission analysis of power generation systems: Japanese case.*Energy.* 30, 2042-2056.

This study presents the results of a life cycle analysis (LCA) of greenhouse gas emissions from power generation systems in order to understand the characteristics of these systems from the perspective of global warming. Nine different types of power generation systems were examined: coal-fired, oil-fired, LNG-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar-photovoltaic (PV). Life cycle greenhouse gas (GHG) emission per kW h of electricity generated was estimated for the systems using a combined method of process analysis and input–output analysis. First, average power generation systems reflecting the current status in Japan were examined as base cases.

Second, the impacts of emerging and future nuclear, wind power and PV technologies were analyzed. Finally, uncertainties associated with some assumptions were examined to help clarify interpretation of the results.

Joshi S., 2000. Product Environmental Life-Cycle Assessment Using Input-Output Techniques. *Journal of Industrial Ecology.* 3(2-3), 95-120.

Life-cycle assessment (LCA) facilitates a systems view in environmental evaluation of products, materials, and processes. Life-cycle assessment attempts to quantify environmental burdens over the entire life-cycle of a product from raw material extraction, manufacturing, and use to ultimate disposal. However, current methods for LCA suffer from problems of subjective boundary definition, inflexibility, high cost, data confidentiality, and aggregation. This paper proposes alternative models to conduct quick, cost effective, and yet comprehensive life-cycle assessments. The core of the analytical model consists of the 498 sector economic input-output tables for the U.S. economy augmented with various sector-level environmental impact vectors. The environmental impacts covered include global warming, acidification, energy use, non-renewable ores consumption, eutrophication, conventional pollutant emissions and toxic releases to the environment. Alternative models are proposed for environmental assessment of individual products, processes, and life-cycle stages by selective disaggregation of aggregate input-output data or by creation of hypothetical new commodity sectors. To demonstrate the method, a case study comparing the life-cycle environmental performance of steel and plastic automobile fuel tank systems is presented.

Keoleian G.A., Blanchard S., Reppe P., 2001. Life-cycle energy, costs, and strategies for improving a single-family house. *Journal of Industrial Ecology.* 4(2), 135-156.

The life-cycle energy, greenhouse gas emissions, and costs of a contemporary 2,450 sqft (228 m3) U.S. residential home (the standard home, or SH) were evaluated to study opportunities for conserving energy throughout pre-use (materials production and construction), use (including maintenance and improvement), and demolition phases. Home construction and maintenance materials and appliances were inventoried totaling 306 metric tons. The use phase ac-

counted for %91 of the total life-cycle energy consumption over a 50- year home life. A functionally equivalent energy-efficient house (EEH) was modeled that incorporated 11 energy efficiency strategies. These strategies led to a dramatic reduction in the EEH total life-cycle energy; 6,400 GJ for the EEH compared to 16,000 GJ for the SH. For energy-efficient homes, embodied energy of materials is important; pre-use energy accounted for %26 of life-cycle energy. The discounted (%4) life-cycle cost, consisting of mortgage, energy, maintenance, and improvement payments varied between $426,700 and $454,300 for a SH using four energy price forecast scenarios. In the case of the EEH, energy cost savings were offset by higher mortgage costs, resulting in total life-cycle cost between $434,100 and $443,200. Life-cycle greenhouse gas emissions were 1,010 metric tons CO_2 *equivalent for an SH and 370 metric tons for an EEH.*

Kondo Y., Nakamura S., 2004. Evaluating alternative life-cycle strategies for electrical appliances by the waste input-output model.*International Journal of Life Cycle Assessment.* 9(4), 236-246.

In 2001, a new law on the recycling of end-of-life electric home appliances (EL-EHA) was put into effect in Japan; it was the first legislation of its sort in the world, and deserves to be called the 'Japan model.' This article is concerned with the LCA of alternative life-cycle strategies for EL-EHA, which consist of recycling as prescribed by the law, 'ecodesign' strategies such as the implementation of design for disassembly (DfD) and the extension of product life (EPL), with and without ex-post functional upgradability, and the once-dominant treatment methods such as landfilling and simple shredding. We use the waste input-output (WIO) analysis, a new method of hybrid LCA that was developed by the authors. The WIO extends the conventional input-output analysis to explicitly take into account the interdependence between the flow of goods and the flow of waste in the whole economy, and hence provides an optimal platform for LCA involving waste treatment and recycling. Furthermore, the WIO enables us to evaluate not only environmental impacts, but also economic impacts such as sectoral output and employment. Our analysis is based on the WIO table for 1995 and detailed process data on recycling. Recycling of EL-EHA, as prescribed by the Japanese law on the recycling of EL-EHA, was found to be effective in reducing CO_2 *emissions, depletion of abiotic resources, generation of waste, and landfill con-*

sumption, provided the rate of retrieval remains at a high level. Our results also indicate the possible effectiveness of eco-design strategy toward the realization of a sustainable economy.

Koornneef J., Keulen T.V., Faaij A., Turkenburg W., 2008. Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. *International Journal of Greenhouse Gas Control.* 2, 448-467.

In this study, the methodology of life cycle assessment has been used to assess the environmental impacts of three pulverized coal fired electricity supply chains with and without carbon capture and storage (CCS) on a cradle to grave basis. The chain with CCS comprises post-combustion CO_2 capture with monoethanolamine, compression, transport by pipeline and storage in a geological reservoir. The two reference chains represent subcritical and state-of-the-art ultra supercritical pulverized coal fired electricity generation. For the three chains we have constructed a detailed greenhouse gas (GHG) balance, and disclosed environmental trade-offs and co-benefits due to CO_2 capture, transport and storage. Results show that, due to CCS, the GHG emissions per kWh are reduced substantially to 243 g/kWh. This is a reduction of 78 and %71 compared to the sub-critical and stateof- the-art power plant, respectively. The removal of CO_2 is partially offset by increased GHG emissions in up- and downstream processes, to a small extent (0.7 g/kWh) caused by the CCS infrastructure. An environmental co-benefit is expected following from the deeper reduction of hydrogen fluoride and hydrogen chloride emissions. Most notable environmental trade-offs are the increase in human toxicity, ozone layer depletion and fresh water ecotoxicity potential for which the CCS chain is outperformed by both other chains. The state-of-the-art power plant without CCS also shows a better score for the eutrophication, acidification and photochemical oxidation potential despite the deeper reduction of SOx and NOx in the CCS power plant. These reductions are offset by increased emissions in the life cycle due to the energy penalty and a factor five increase in NH3 emissions.

Lave L.B., Cobas-Flores E., Hendrickson C.T., McMichael F.C., 1995. Using I-O analysis to estimate economy-wide discharges. *Environmental Science and*

Technology. 29(9), 420-426.

Life-cycle assessment models attempt to quantify the environmental implications of alternative products and processes, tracing pollution discharges and resources use through the chain of producers and consumers. Present life-cycle assessments must draw boundaries that limit consideration to a few producers in the chain from raw materials to a finished product. We show that this limitation considers only a fraction of the environmental discharges associated with a product or process, thereby making current assessments unreliable. We propose an approach that uses economic input-output analysis and pollution discharge data and apply the model to automobiles, refrigerators, and computer purchases, and to a comparison of paper and plastic cups.

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

Conventional process-analysis-type techniques for compiling life-cycle inventories suffer from a truncation error, which is caused by the omission of resource requirements or pollutant releases of higher-order upstream stages of the production process. The magnitude of this truncation error varies with the type of product or process considered, but can be on the order of %50. One way to avoid such significant errors is to incorporate input-output analysis into the assessment framework, resulting in a hybrid life-cycle inventory method. Using Monte-Carlo simulations, it can be shown that uncertainties of input-output based life-cycle assessments are often lower than truncation errors in even extensive, third-order process analyses.

Lenzen M., 2009. Dealing with double-counting in tiered hybrid life-cycle inventories: a few comments.*Journal of Cleaner Production.* 17, 1382-1384.

Stromman et al. (2009) developed a method for dealing with double-counting in tiered hybrid LCA. Their algorithms identify overlaps of physical and monetary flows in the process and input–output parts of their hybrid data base, and then remove double-counted monetary flows in the input–output system using structural path analysis. Stromman's adjustment criterion is that the set of input-output paths to be removed should have the same monetary value as the process system *flow that it overlaps with. I comment on Stromman's methods with respect to the accuracy of the correspondence between process and input–output systems. I argue that the set of double-counted paths to be removed from the input-output system is better selected on the basis of sector definitions than monetary value.*

Lenzen M., Dey C., 2000. Truncation error in embodied energy analyses of basic iron and steel products. *Energy.* 25, 577-585.

An input-output study of the energy requirements for the manufacture of basic iron and steel products by the Australian steel industry is presented. The basis of this study is a decomposition of the total energy requirement per mass output of steel into partial requirements from industry sectors supplying the steel industry. A separation into different order requirements shows that lower order energy requirements for basic iron and steel, chosen from the supplying industries identified in a recent process analysis, are 19 *MJ/kg, and that the total energy requirement is* 40.1 *MJ/kg. This proportion demonstrates that truncation error in this process analysis, that is, the omission of higher order energy contributions, is of the order of %50.*

Lenzen M., Munksgaard J., 2002. Energy and CO_2 life-cycle analysis of wind turbines — review and applications. *Renewable Energy.* 26, 339-362.

Despite the fact that the structure and technology of most modern wind turbines differs little over a wide range of power ratings, results from existing life-cycle assessments of their energy and CO_2 intensity show considerable variations. While the range of energy intensities reflects economies of scale, their scatter is due to discrepancies in the energy contents of materials and the analyses' methodology and scope. Furthermore, energy intensities depend crucially on the country of manufacture, turbine recycling or overhaul after the service life, and the choice of tower material. In addition, CO_2 intensities vary with national fuel mixes. Measures of life-cycle energy or CO_2 emissions can be employed in policy and planning, especially for comparative risk and sustainability assessments, and source switching and capacity growth scenarios. If these measures are to assist decision-making, uncertainties in life-cycle assessments should be minimised by compliance to a standardised methodology, and by use of input–output-based

hybrid techniques.

Lenzen M., Treloar G., 2002. Differential convergence of life-cycle inventories toward upstream production layers. *Journal of Industrial Ecology.* 6(3-4), 137-160.

We present an input-output analysis of the life-cycle labor, land, and greenhouse gas (GHG) requirements of alternative options for three case studies: investing money in a new vehicle versus in repairs of an existing vehicle (labor), passenger transport modes for a trip between Sydney and Melbourne (land use), and renewable electricity generation (GHG emissions). These case studies were chosen to demonstrate the possibility of rank crossovers in life-cycle inventory (LCI) results as system boundaries are expanded and upstream production inputs are taken into account. They demonstrate that differential convergence can cause crossovers in the ranking of inventories for alternative functional units occurring at second- and higher order upstream production layers. These production layers are often excluded in conventional process-type life-cycle assessment (LCA) by the delineation of a finite system boundary, leading to a systematic truncation error within the LCI. The exclusion of higher-order upstream inputs can be responsible for ranking crossovers going unnoticed. In this case, an incomplete conventional process-type LCA of two alternative options can result in preferences and recommendations to decision makers that are different from preferences and recommendations concluded from a complete hybrid input output-based assessment. Therefore, the need to avoid misleading effects on the ranking of alternative functional units due to differential convergence supports the practice of hybrid input-output-based LCA techniques.

Lenzen M., Treloar G., 2002. Embodied energy in building: wood versus concrete — reply to Borjesson and Gustavsson. *Energy Policy.* 30, 249-255.

We analyse the wood and concrete designs of the Walludden building described by Borjesson et al. (Energy Policy 28 (2000) 575) in terms of their embodied energy, employing an environmentally extended input–output framework in a tiered hybrid life-cycle assessment, and in a structural path analysis. We illustrate the complexity of the inter-industry supply chains underlying the upstream energy requirements for the building options, and demonstrate that higher-order *inputs are difficult to capture in a conventional process analysis. Our calculations show that Borjesson and Gustavsson's estimates of energy requirements and greenhouse gas emissions are underestimated by a factor of about 2, and that corresponding greenhouse gas balances are positive at about 30 t C-eq. Nevertheless, Borjesson and Gustavsson's general result the concrete-framed building causing higher emissions still holds.*

Menzies G.F., Turan S., Banfill P.F.G., 2007. Life-cycle assessment and embodied energy: a review. *Construction Materials.* 160, 135-143.

In this paper life-cycle assessment (LCA) is studied and a brief review and classification of databases and inventories is given. The factors affecting the dissimilar results in various databases are examined and discussed. The main obstacles to LCA and life-cycle energy studies, and their sources, are discussed, together with the role of data in inventory analysis. Embodied energy results are reviewed and compared, and the causes of dissimilarities and variations in these studies are presented. This paper focuses on methodologies developed and adopted for data processing, and inventory analysis for building materials. The data-LCA relationship is investigated, and the importance and role of data in LCA is reviewed. A case study of steel as a building material is introduced and a number of life cycle energy assessment studies are evaluated. The paper concludes by outlining a number of issues which need to be handled with care when performing a life-cycle study, and which warrant further qualitative and quantitative analysis.

Moriguchi Y., Kondo Y., Shimizu H., 1993. Analyzing the life cycle impacts of cars: the case of CO_2. *Industry and Environment.* 16(1-2), 42-45.

Automobiles have various environmental impacts. Their life cycle includes raw materials production, assembly, use and maintenance, and final disposal. The impacts of the construction and maintenance of road infrastructure also have to be considered. As an example of the quantitative analysis of life cycle environmental impacts, CO_2 *emissions from the production and use of automobiles can be estimated using the summing-up approach and the input-output analysis approach. This article also reviews recent topics related to automobile production and use in Japan including the development of electrically powered automobiles*

and automobile bodies with a high aluminum content.

Munksgaard J., Wier M., Lenzen M., Dey C., 2005. Using input-output analysis to measure the environmental pressure of consumption at different spatial levels. *Journal of Industrial Ecology.* 9(1-2), 169-185.

Input-output modeling is a useful tool for tracing environmental impacts of consumption. Because it includes impacts originating from production layers of infinite order (capturing the entire economy), input-output modeling is highly relevant for studies operating in a life-cycle context. In this article, we show how the input-output approach can be used to enumerate the problem of sustainable consumption. Based on a literature survey including research done by the authors we present measures of the emissions of carbon dioxide at different spatial levels: nation, city, and household. Further, we take more environmental effects into account and introduce the concept of environmental efficiency by combining input-output modeling and data envelopment analysis. Finally, we discuss the policy relevance of the different measures. The article demonstrates that input-output modeling has a wide range of life-cycle oriented applications when combined with other data sources such as detailed trade statistics, foreign input-output and environmental statistics, and household expenditure data.

Ochoa L., Hendrickson C., Matthews H.S., 2002. Economic input-output life-cycle assessment of U.S. residential buildings. *Journal of Infrastructure Systems.* 8(4), 132-138.

We estimate the building resource requirements, electricity and energy used, greenhouse gas releases, hazardous waste generated, and toxic air releases for the construction, usage, and demolition of typical U.S. residences in 1997. Within the three phases, usage (%54 of economic activity) is the largest consumer of electricity (%95) and energy (%93) and the largest emitter of greenhouse gases (%92), while the construction phase (%46 of economic activity) is the largest air toxics emitter (%57) and contributes %51 of hazardous waste. The disposal phase contribution is negligible in all of these categories. From the standpoint of the entire U.S. economy, residential buildings account for %5.3 of the Gross Domestic Product, %38 of electricity consumption, %26 of energy consumption, %24 of greenhouse gas emissions, %26 of hazardous waste, and %12 of toxic air *emissions. We comment on possible remedial actions— including some current public policies—to address environmental impacts.*

Odeh N.A., Cockerill T.T., 2008. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy.* 36, 367-380.

The evaluation of life cycle greenhouse gas emissions from power generation with carbon capture and storage (CCS) is a critical factor in energy and policy analysis. The current paper examines life cycle emissions from three types of fossil-fuel-based power plants, namely supercritical pulverized coal (super-PC); natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC), with and without CCS. Results show that, for a %90 CO_2 *capture efficiency, life cycle GHG emissions are reduced by %(75–84) depending on what technology is used. With GHG emissions less than 170 g/kWh, IGCC technology is found to be favorable to NGCC with CCS. Sensitivity analysis reveals that, for coal power plants, varying the* CO_2 *capture efficiency and the coal transport distance has a more pronounced effect on life cycle GHG emissions than changing the length of* CO_2 *transport pipeline. Finally, it is concluded from the current study that while the global warming potential is reduced when MEA-based* CO_2 *capture is employed, the increase in other air pollutants such as NOx and NH3 leads to higher eutrophication and acidification potentials.*

Peters G.P., Hertwich E.G., 2006. A comment on "Functions, commodities and environmental impacts in an ecological-economic model." *Ecological Economics.* 59, 1-6.

In a recent paper in this journal, Suh [Suh, S., 2004. Functions, commodities and environmental impacts in an ecological-economic model. Ecological Economics 40 (4), 451-467.] 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 use of the integrated hybrid LCA approach. In particular, the interpretation of the downstream feedback term, Cd, is discussed with particular focus on practical implementation. In this paper, two interpretations of Cd are suggested depending on the particular LCA data used. If the LCA data is designed for a demand on the functional unit only, then it is argued that the Cd term is negligible in many applications.

If the LCA data is compatible with an arbitrary demand, then it is argued that in many cases the consistent use of the Cd term implies data requirements that may not be justified by the potential gains.

Rebitzer G., Ekvall T., Frischknecht R., Hunkeler D., Norris G., Rydberg T., Schmidt W.P., Suh S., Weidema B.P., Pennington D.W., 2004. Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environmental International.* 30, 701-720.

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for the provision of goods and services (both of which are summarized under the term "products"). Environmental impacts include those from emissions into the environment and through the consumption of resources, as well as other interventions (e.g., land use) associated with providing products that occur when extracting resources, producing materials, manufacturing the products, during consumption/use, and at the products' end-of-life (collection/sorting, reuse, recycling, waste disposal). These emissions and consumptions contribute to a wide range of impacts, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise—among others. A clear need, therefore, exists to be proactive and to provide complimentary insights, apart from current regulatory practices, to help reduce such impacts. Practitioners and researchers from many domains come together in life cycle assessment (LCA) to calculate indicators of the aforementioned potential environmental impacts that are linked to products—supporting the identification of opportunities for pollution prevention and reductions in resource consumption while taking the entire product life cycle into consideration. This paper, part 1 in a series of two, introduces the LCA framework and procedure, outlines how to define and model a product's life cycle, and provides an overview of available methods and tools for tabulating and compiling associated emissions and resource consumption data in a life cycle inventory (LCI). It also discusses the application of LCA in industry and policy making. The second paper, by Pennington et al. (Environ. Int. 2003, in press), highlights the key features, summarizes available approaches, and outlines the key challenges of assessing *the aforementioned inventory data in terms of contributions to environmental impacts (life cycle impact assessment, LCIA).*

Spivak A., 2011. A theoretical model for life cycle inventory analysis using a disaggregated hybrid methodology. Theses and Dissertations. The University of Toledo.

Methodologies used to calculate life cycle inventory (LCI) of the functional unit have been developed since the 1970's to include hybrids of process analysis and input-output methods. Most of the current techniques do not take into account the usage of the product and end of life product aspects, or limit such applications (e.g. Method V of Tiered Hybrid LCI). The goal of this dissertation is to introduce a comprehensive method that takes strong consideration of inventory costs of use and end of life of the functional unit by combining manufacturing and demanufacturing into the centerpiece of the hybrid analysis. In order to obtain this goal, a new disaggregated methodology is constructed by enhancing currently developed hybrid methods of life cycle inventory compilations. The new methodology is then compared to existing methodologies and to ISO14040 standards. The results of the sample calculations have shown that under right conditions use of disaggregated method will result in significant changes (lowest experimental result: %17 change in CO_2 *equivalent). The theoretical comparison of ISO14040 requirements had proved that disaggregated hybrid is at least as good on some areas and better in other areas then currently accepted hybrid methods.*

Stromman A.H., Peters G.P., Hertwich E.G., 2009. Approaches to correct for double counting in tie Acquaye A.A., Wiedmann T., Feng K., Crawford R.H., Barrett J., Kuylenstierna J., Duffy A.P., Koh L., McQueen-Mason S., 2011. Identification of 'Carbon Hot-Spots' and Quantification of GHG Intensities in the Biodiesel Supply Chain Using Hybrid LCA and Structural Path Analysis. *Environmental Science and Technology*. 45, 2471-2478.

This paper presents an approach for inventory compilation and adjustment of double counting in tiered hybrid life cycle inventories (LCIs). The combination of input–output and physical inventory data on coefficient level is a convenient way of constructing a hybrid LCI that has both good detail and completeness.

The proposed approach formalizes how to deal with partially overlapping data in inventory compilation. This particular approach requires that the issue of double counting is resolved in a consistent manner. Algorithms for identifying and adjusting for double counting are developed. Identification is performed based on a structural path analysis (SPA). Two algorithms for adjustment are presented. The first method is relatively simple to implement but has limitations to its applicability when performing a detailed assessment. The second method is more complex to implement but provides results that allow for more comprehensive structural inventory analysis. Numerical examples are provided in Appendix.

Stromman A.H., Solli C., 2008. Applying Leontief's price model to estimate missing elements in hybrid life cycle inventories.*Journal of Industrial Ecology.* 12(1), 26-33.

This article presents an approach to estimate missing elements in hybrid life cycle inventories. Its development is motivated by a desire to rationalize inventory compilation while maintaining the quality of the data. The approach builds on a hybrid framework, that is, a combination of process- and input– output-based life cycle assessment (LCA) methodology. The application of Leontief 's price model is central in the proposed procedure. Through the application of this approach, an inventory with no cutoff with respect to costs can be obtained. The formal framework is presented and discussed. A numerical example is provided in Supplementary Appendix S1 on the Web.

Suh S., 2004. Functions, commodities and environmental impacts in an ecological economic model. *Ecological Economics.* 48, 451-467.

In contrast to macroscopic tools, life cycle assessment (LCA) starts from the microstructure of an economic system: the production and consumption of functional flows. Due to the level of resolution required for function-level details, the model used for LCA has relied on process-specific data and has treated the product system as a stand-alone system instead of a system embedded within a broader economic system. This separation causes various problems, including incompleteness of the system and loss of applicability for a variety of analytical tools developed for LCA or economic models. This study aims to link the functional flow-based, micro-level LCA system to its embedding, commodity-

based, meso- or macro-level economic system represented by input–output accounts, resulting in a comprehensive ecological–economic model within a consistent and flexible mathematical framework. For this purpose, the LCA computational structure is reformulated into a functional flow by process framework and reintroduced in the context of the input–output tradition. It is argued that the model presented here overcomes the problem of incompleteness of the system and enables various analytical tools developed for LCA or input– output analysis (IOA) to be utilized for further analysis. The applicability of the model for cleaner production and supply chain management is demonstrated using a simplified product system and structural path analysis as an example.

Suh S., 2006. Reply: downstream cut-offs in integrated hybrid life cycle assessment. Ecological Economics. 59, 7-12.red hybrid life cycle inventories. *Journal of Cleaner Production.* 17, 248-254.

In the comment by Peters and Hertwich (Peters, G.P., Hertwich, E., 2006-this issue), the authors provide two interpretations on one of the block matrices that is a part of the integrated hybrid Life Cycle Assessment (LCA) framework presented in Suh (2004a) (Suh, S., 2004a. Functions, commodities and environmental impacts in an ecological economic model. Ecological Economics 48 (4), 451–467). The authors argue that the contribution of the downstream cut-off matrix to the overall results might be small, or the amount of resources needed to compile the matrix will be too high, depending on the type of the LCA databases that the authors distinguish. In this response, I confirm that the contribution of the downstream cut-off matrix is generally minor, which can be easily recognized from the structure of the system. However, one should realize that there are the cases when it is not, leaving little reason to automatically pre-set the downstream cut-off matrix as a zero matrix. A set of conditions under which a downstream cut-off matrix becomes an important part is discussed, and a practical method for checking the potential importance of a downstream cut-off matrix before actually compiling data is presented. The method is tested using the numerical example shown in Suh (2004a). The distinction of LCA databases based on their capabilities of handling arbitrary demands, which is proposed by Peters and Hertwich, is discussed from an LCA practitioner's point of view, and it is argued that the actual process of data collection for the downstream cut-off

matrix is far from what the authors suggest. Finally, a stepwise strategy for an efficient data collection under the budget and time constraints is discussed.

Suh S., Huppes G., 2002. Missing inventory estimation tool using extended input-output analysis. *The International Journal of Life Cycle Assessment.* 7(3), 134-140.

Input-output analysis (IOA) has recently been introduced to Life Cycle Assessment (LCA). In applying IOA to LCA studies, however, it is important to note that there are both advantages and disadvantages. This paper aims to provide a better understanding of the advantages and disadvantages of adopting IOA and LCA, and introduces the methodology and principles of the Missing Inventory Estimation Tool (MIET) as one of the approaches to combine the strengths of process-specific LCA and IOA. Additionally, we try to identify a number of possible errors in the use of IOA and LCA purposes, due to confusion between industry output and commodity, consumer's price and producer's price. MIET utilizes the 1996 US input-output table and various environmental statistics. It is based on an explicit distinction between commodity and industry output. MIET is a self-contained, publicly available database which can be applied directly in LCA studies to estimate missing processes. By adopting MIET results in existing, process-based, life-cycle inventory (LCI), LCA practitioners can fully utilize the process-specific information while expanding the system boundary. MIET will be continuously updated to reflect both methodological developments and newly available data sources.

Suh S., Huppes G., 2005. Methods for life cycle inventory of a product. *Journal of Cleaner Production.* 13(7), 687-697.

Methods for Life Cycle Inventory (LCI) compilation are reviewed and compared. In total, six methods are distinguished. They are LCI computation using process flow diagram; matrix expression of product system; input-output (IO) based LCI; and three different forms of hybrid analysis: the tiered hybrid analysis, the IO-based hybrid analysis, and the integrated hybrid analysis. Theory and principles of these methods are presented using a numerical example, and evaluated with regard to data requirements, uncertainty of source data, upstream system boundary, technological system boundary, geographical system boundary, avail-

able analytical tools, time and labour intensity, simplicity of application, required computational tools and available software tools. Compliance of these methods to ISO standards is discussed. Finally, conclusions are drawn, combined with a view on the future outlook of these inventory building methods.

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

Life-cycle assessment (LCA) is a method for evaluating the environmental impacts of products holistically, including direct and supply chain impacts. The current LCA methodologies and the standards by the International Organization for Standardization (ISO) impose practical difficulties for drawing system boundaries; decisions on inclusion or exclusion of processes in an analysis (the cutoff criteria) are typically not made on a scientific basis. In particular, the requirement of deciding which processes could be excluded from the inventory can be rather difficult to meet because many excluded processes have often never been assessed by the practitioner, and therefore, their negligibility cannot be guaranteed. LCA studies utilizing economic input-output analysis have shown that, in practice, excluded processes can contribute as much to the product system under study as included processes; thus, the subjective determination of the system boundary may lead to invalid results. System boundaries in LCA are discussed herein with particular attention to outlining hybrid approaches as methods for resolving the boundary selection problem in LCA. An input-output model can be used to describe at least a part of a product system, and an ISO-compatible system boundary selection procedure can be designed by applying hybrid input-output assisted approaches. There are several hybrid input output analysis-based LCA methods that can be implemented in practice for broadening system boundary and also for ISO compliance.

Treloar G.J., 1997. Extracting embodied energy paths from input-output tables: towards an input-output based hybrid energy analysis method. *Economic Systems Research.* 9(4), 375-391.

Embodied energy is defined as the energy consumed in all activities necessary

to support a process, including upstream processes. The Leontief inverse input-output (IO) matrix gives results that are practically complete, because of the aggregation of direct and indirect requirements, but which are also unreliable, because of inherent assumptions. Although accurate for the system boundary considered, process analysis results are incomplete relative to the pure IO system boundary. Attempts to combine process and IO analysis tend to be based on process analysis data. The system boundary is still significantly incomplete-although not as incomplete as for pure process analysis. An IO-based hybrid analysis technique that requires the extraction of particular paths from the direct IO matrix has been developed. The potential for embodied energy paths to be used as the basis for a hybrid analysis of the Australian residential building sector is discussed. The results indicate that less than three-quarters of the total embodied energy of this sector is likely to be able to be validated, because of the complexity of the embodied energy paths.

Treloar G.J., 1998. A comprehensive embodied energy analysis framework. Ph.D. Thesis. Deakin University, Geelong.

Embodied energy is the energy required directly and indirectly to manufacture products. Its analysis requires data on energy use and upstream requirements for other products. However, previous industry-based methods of embodied energy analysis are incomplete in framework. Previous national statistical methods, while comprehensive, are a 'black box', subject to errors. A new method is derived involving the decomposition of a national statistical model to allow more reliable industry data to be integrated. The method is demonstrated for an individual residential building, showing that—for many products—more types of industry data may need to be derived than previously thought.

Treloar G.J., Love P.E.D., Holt G.D., 2001. Using national input-output data for embodied energy analysis of individual residential buildings. *Construction Management and Economics*. 19, 49-61.

Embodied energy (EE) analysis has become an important area of energy research, in attempting to trace the direct and indirect energy requirements of products and services throughout their supply chain. Typically, input-output (I-O) models have been used to calculate EE because they are considered to be comprehensive *in their analysis. However, a major deficiency of using I-O models is that they have inherent errors and therefore cannot be reliably applied to individual cases. Thus, there is a need for the ability to disaggregate and I-O model into its most important 'energy paths', for the purpose of integrating case-specific data. This paper presents a new hybrid method for conducting EE analyses for individual buildings, which retains the completeness of the I-O model. This new method is demonstrated by application to an Australian residential building. Only %52 of the energy paths derived from the I-O model were substituted using case-specific data. This indicates that previous system boundaries for EE studies of individual residential buildings are less than optimal. It is envisaged that the proposed method will provide construction professionals with more accurate and reliable data for conducting life cycle energy analysis of buildings. Furthermore, by analyzing the unmodified energy paths, further data collection can be prioritized effectively.*

Treloar G.J., Love P., Faniran O., 2001. Improving the reliability of embodied energy methods for project life-cycle decision making. *Logistic Information Management.* 14(5-6), 42-45.

Embodied energy is the total amount of energy required to produce a product, and is significant because it occurs immediately and can be equal over the life cycle of a building to the transient requirements for operational energy. Methods for embodied energy analysis include process analysis, input-output analysis and hybrid analysis. Proposes to improve the reliability of estimating embodied energy based on input-output models by using an algorithm to extract systematically the most important energy paths for the "other construction" sector from an Australian input-output model. Demonstrates the application of these energy paths to the embodied energy analysis of an individual commercial building, highlighting improvements in reliability due to the modification of energy paths with process analysis data. Compares materials and elements for the building, and estimates likely ranges of error.

Wiedmann T.O., Suh S., Feng K., Lenzen M., Acquaye A., Scott K., Barrett J.R., 2011. Application of hybrid life cycle approaches to emerging energy technologies – the case of wind power in the UK. *Environmental Science and*

Technology. 45, 5900-5907.

Future energy technologies will be key for a successful reduction of man-made greenhouse gas emissions. With demand for electricity projected to increase significantly in the future, climate policy goals of limiting the effects of global atmospheric warming can only be achieved if power generation processes are profoundly decarbonized. Energy models, however, have ignored the fact that upstream emissions are associated with any energy technology. In this work, we explore methodological options for hybrid life cycle assessment (hybrid LCA) to account for the indirect greenhouse gas (GHG) emissions of energy technologies using wind power generation in the UK as a case study. We develop and compare two different approaches using a multi-region input-output modeling framework, Input-Output-based Hybrid LCA and Integrated Hybrid LCA. The latter utilizes the full-sized Ecoinvent process database. We discuss significance and reliability of the results and suggest ways to improve the accuracy of the calculations. The comparison of hybrid LCA methodologies provides valuable insight into the availability and robustness of approaches for informing energy and environmental policy.

Zapata P., Gambatese J.A., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction. *Journal of Infrastructure Systems.* 11(1), 9-20.

In addition to traditional economic and technical objectives, environmental impact, and sustainability are increasingly being considered in the design of roadways and other infrastructure projects. This paper presents an abbreviated life cycle inventory assessment of a continuously reinforced concrete pavement (CRCP) and an asphalt pavement with respect to the energy consumed by each pavement type for the construction of a roadway. For CRCP, energy is primarily consumed during the manufacture of cement and reinforcing steel, which together account for approximately %94 of the total amount of energy consumed from extraction of raw materials through placement of the CRCP. For asphalt pavement, the major consumption of energy from extraction through placement occurs during asphalt mixing and drying of aggregates (%48) and the production of bitumen (%40). The assessment results highlight where sustainable design efforts to reduce energy consumption can best be directed in the initial phases of

a pavement's life cycle.