Estimating Construction Project Environmental Effects Using an Input-Output-Based Hybrid Life-Cycle Assessment Model

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Abstract: The design and construction industries have an increasing interest in and responsibility for a building's environmental effects over its entire life cycle. Quantification of all building phases is important in life-cycle assessments (LCAs), especially for the construction phase, which is often disregarded. This research uses an input-output-based LCA framework to create a more comprehensive estimate of the environmental effects of construction processes. The hybrid LCA model is based on Carnegie Mellon University's Economic Input-Output Life Cycle Assessment (EIO-LCA) tool and combines a new EIO-LCA "hybrid" interface with updated and reformulated environmental effect vectors for EIO-LCA's 13 construction sectors. Eight construction project case studies modeled on the input-output (I-O)-based hybrid LCA framework demonstrate the model's broad applicability; gasoline, particulate matter, and global warming potential effects generally increased across all construction sectors and case studies. The I-O-based hybrid LCA model for construction is intended to help decision makers make more informed decisions regarding the construction industry, adding environmental quality and sustainable development as project goals instead of unintentional benefits of economic decisions.

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Introduction

As a prevalent fixture around the world and an economic indicator of the United States economy, the economic effects of the construction industry are 5% of the U.S. gross domestic product (GDP) (DOC 2005b). Also, per the Bureau of Economic Analysis (BEA), the construction industry had one of the higher industry growth rates between 1997 and 2002 (an average of 6% annually) (Stanley-Allen et al. 2005). Because the construction industry is a major force in the national and global economy, it is imperative that building industry stakeholders address the issue of construction sustainability. However, as the building industry has been undergoing a "green revolution" with the growth of "green building," few holistic sustainable practices have been applied to the construction industry itself.

Much of the current sustainability and life-cycle assessment focus within the green building movement concentrates on building materials and products; the majority of past building research has focused on the environmental effects of material selection, building energy use, and/or indoor environmental quality (Gambatese and Rajendran 2005; Horvath 2004; Lee and Chang 2000; Lippiatt and Norris 1995; Osman and Ries 2003). While these effects are important, the construction industry itself is also responsible for many environmental impacts, primarily air emissions, land use, waste generation, water use and discharges, and energy use and demand (Bilec et al. 2006; Ochoa et al. 2002). However, most life-cycle assessments (LCAs) either ignore or negate the construction phase of infrastructure projects (Sharrard 2007). If the *entire* life cycle of a structure is ever to be truly quantified, a LCA of the construction phase of a project must be performed to help place construction's environmental effects in context with the rest of the building life cycle.

Consequently, this research focuses on the efficiency, economic effect, and environmental impact of construction activities, *not* construction materials or operational impacts. Only through completely analyzing the economic costs and environmental effects of on-site construction can we move past the simple construction analysis that the green building standards like the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) have started and towards a complex building LCA model that incorporates the site, construction, skeleton, interior, operation, and maintenance aspects of creating a structure.

Past building LCAs have used existing underestimations of construction activity instead of evaluating the construction process itself in terms of environmental effects (Junnila and Horvath 2003; Keoleian et al. 2001; Ochoa et al. 2002). This problem is common to environmental effects from all types of infrastructure, not just constructed facilities. Because the environmental effects of the construction site have never been adequately quantified, the

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assumption that the effects of construction are negligible in comparison with the other building phases is supposition based on the status quo. Consequently, many existing decision models ignore the environmental effects of infrastructure construction because these impacts were assumed to be negligible at the start of many assessments.

The input-output-based hybrid LCA model described herein attempts to address this problem. Thus, even if the environmental effects from infrastructure and construction are small compared to building operation, these impacts may be large when analyzed in a different time frame or as a function of all buildings (i.e., effects per day instead or a sum of all construction events, respectively). Additionally, the model described here attempts to serve infrastructure stakeholders interested in creating a more sustainable construction industry more suitably than other less construction-focused LCA tools. As a result, this input-output-based LCA model is in the public domain ⟨http://www.eiolca.net/aurora-hybrid.html⟩ (Sharrard and Matthews 2007b), useable with existing construction project information, and comparable to other estimation methods.

Life-Cycle Assessment Background

One tool available to assess and manage the environmental effects of the construction process is life-cycle assessment. LCA is a decision-support tool that holistically estimates the environmental effects of a product, process, or activity by evaluating its entire life (commonly referred to as cradle-to-grave, cradle-to-cradle, or cradle-to-gate modeling). LCA also presents the economic and environmental effects of various processes, while assessing the topic being considered in terms of global, national, and regional social and environmental impacts.

The two primary LCA methods are process LCA and input-output (I-O) LCA (Fava et al. 1991; Hendrickson et al. 2006). Because the construction industry is so complex, modeling construction processes in order to better understand their environmental implications would be best achieved with the process LCA approach. However, process LCAs are data intensive and time consuming given the unique nature of construction projects. Current process LCA models either ignore, underestimate, or inadequately address the environmental effects of the construction process (NIST 2004; NREL 2006; PE Consulting Group 2004; Pre 2007; Sharrard 2007). ATHENA is the exception, although the specifics of their construction phase impact calculations are not accessible (Athena Institute 2006).

Conversely, the I-O LCA approach allows for a more inclusive view of the construction industry (i.e., on-site construction activities *and* its supply chain), which can be used to identify processes of principal concern. Because data collection for I-O LCA models must be performed on a national level, there are only a few operating (Hayami et al. 1997; Lenzen 1998; Pesonen et al. 2000). The I-O tool of focus for this research is Carnegie Mellon University's Economic Input-Output Life Cycle Assessment tool (EIO-LCA), which models the United States economy (CMU GDI 2007; Hendrickson et al. 2006). Though large in scale, the existing EIO-LCA modeling scheme for the construction industry is simplified and underestimates environmental discharges; this situation was the impetus for creation of a hybrid model for construction (Hendrickson and Horvath 2000; Sharrard 2007).

Both the process and input-output LCA methods have strengths and weaknesses; thus, combining the two methods into a hybrid capitalizes on each method's LCA modeling assets (Suh et al. 2004). More recent hybrid construction LCAs have led the way toward more accurate assessments of construction's environmental effects, mostly for commercial buildings (Bilec et al. 2006; Guggemos and Horvath 2005; 2006; Junnila and Horvath 2003). This particular research combines the process and I-O LCA methods into an I-O-based hybrid LCA tool that produces a comprehensive analysis that includes economywide effects in addition to on-site construction activities (Joshi 1999).

Methods for Input-Output-Based Life-Cycle Assessment Model

The I-O-based hybrid LCA for the construction industry operates through the existing EIO-LCA interface, but provides the user with access to updated and reformulated environmental effects vectors for the 13 EIO-LCA construction sectors through a new "Hybrid" EIO-LCA feature. This feature can be utilized with all EIO-LCA sectors, but is demonstrated in this research with the construction sectors only. More information on the 13 construction sectors can be obtained from the main EIO-LCA website (CMU GDI 2007; Hendrickson et al. 2006; Sharrard 2007); seven of these sectors are listed in Table 1.

Updating and Reformulating EIO-LCA Environmental Effect Vectors

The current EIO-LCA model employs the most recent United States Department of Commerce 491×491 input-output matrix (1997 benchmark), auxiliary files with energy and resource consumption, and national-level environmental data (Lawson et al. 2002). The reformulated and updated EIO-LCA effect vector is composed of mostly 2002 data (in preparation for EIO-LCA's upcoming update to the 2002 benchmark model). Table 2 summarizes the sources and years of the construction sector environmental effect vector data; bold entries differ from the data sources and years used for the existing 1997 benchmark EIO-LCA model, though effect vectors dependent upon all nonbolded Table 2 cells were double checked for accuracy, reformulated, remapped, and updated (Sharrard 2007). Because no changes have or will be made to the economic interactions of EIO-LCA's construction sectors (i.e., the "direct" or "*A*" matrix), all case study comparisons reflect changes that are a direct result of the effect vector changes and data hybridization; the latter is subsequently described in greater detail, but incorporates utilizing process-level data to adjust sector supply chains.

Many of the data sources listed in Table 2 (and used in creating the EIO-LCA effect vector) organize environmental information by Standard Industrial Classification (SIC) or North American Industry Classification System (NAICS) code; first much of the data had to be converted to the appropriate 1997 I-O categorization scheme. An existing bridge between SIC and NAICS codes was utilized (U.S. Census Bureau 2000). However, though it has one for all other industries, the Census Bureau does not have a map between the NAICS construction industries and the I-O construction sectors for the construction industry (Lawson et al. 2002). To produce a traceable connection between the 28 NAICS 1997 construction industries and the 13 I-O 1997 construction sectors, a construction sector map (CSM) was created; the final CSM is a matrix that includes the percentage of each I-O sector in each NAICS industry (and vice versa) (Sharrard 2007).

While the CSM could be used as a bridge between 1997 NAICS and 1997 I-O codes, some newer data used to update the

Table 1. Case Studies Modeled with I-O-Based Hybrid LCA Framework (Sharrard 2007)

1997 I-O sector		Case study	
Code	Description	Name	Data source
230110	New residential one-unit structure, nonfarm	Ochoa Residential	(Ochoa Franco 2004; Ochoa et al. 2005)
230120	New multifamily housing structures, nonfarm	New House Dormitory	Carnegie Mellon University
230220	Commercial and institutional buildings	Junnila/Guggemos U.S. Office Building RAND interior outfit	(Guggemos, personal communication;[a] Junnila et al. 2006) RAND
230230	Highway, street, bridge, and tunnel construction	Asphalt paving	Virginia Department of Transportation
230320	Maintenance and repair of nonresidential buildings	300 South Craig Street renovation	Carnegie Mellon University
230330	Maintenance and repair of highways, streets, bridges, and tunnels	Bridge superstructure replacement	Pennsylvania Turnpike
230340	Other maintenance and repair construction	Northside Business District Lighting Project	Urban Redevelopment Authority of Pittsburgh

[a]A. Guggemos, "Guggemos—Data for Sharrard," personal communication via e-mail, October 14, 2006.

construction effect vectors were available only in the 2002 NAICS categorization system. A bridge between the 2002 and 1997 NAICS construction codes was used for this purpose (U.S. Census Bureau 2006).

The detailed methods used to update and restructure the construction effect vector for each of the five environmental sections [energy, global warming potential (GWP), conventional air pollutants, and toxic releases] are summarized elsewhere (Sharrard 2007). For each of these categories, a reformulated and updated EIO-LCA effect vector for the construction sectors has been created for both the 1997 NAICS and 1997 I-O codes. Previously, no NAICS effect vector existed (or is useable in the existing EIO-LCA format) because it is an intermediate vector.

Fig. 1 displays the methodological differences between the existing and reformulated energy effect vectors; the main difference included allocating on-road gasoline and diesel use to the construction industry (Sharrard et al. 2007). Future work includes determining which I-O sectors energy and emission levels will decrease as a result of this reallocation to the construction industries; this assessment will be performed when the entire EIO-LCA model is updated to the 2002 benchmark model, in late 2007.

The other major change in effect, vector reformulation, was the inclusion of construction industry fugitive dust (Sharrard 2007). The existing EIO-LCA criteria air pollutant (CAP) effect vector does not include fugitive dust emissions for any EIO-LCA sectors, let alone the construction sectors (Cicas et al. 2005). Given that the construction industry is a large fugitive dust emitter in the 2003 NAQET report, fugitive dust was allocated to the construction industry in the reformulation of the CAP effect vector (EPA 2004).

Hybrid EIO-LCA Feature

The new EIO-LCA-based "hybrid" feature allows hypothetical custom product / process sectors to be created. These hybrid sectors are then simulated within the EIO-LCA model. This hybrid feature instructs users to select the existing EIO-LCA sector that most closely approximates the product or process they want to model. The framework then allows the user to manipulate the actual EIO-LCA direct matrix to create a modified direct supply chain for their custom product. This feature allows the user to make as many or as few changes to the chosen I-O sector as necessary, while comparing their hybrid customized product/process to the base sector they are modifying.

This top-down method provides the user with supply chain values to build from, versus a bottom-up approach that would

Table 2. Reformulated EIO-LCA Construction Sector Environmental Effect Vector Data Sources

	Data		
	Year	Source	Reference
Energy	**2002**	**American FactFinder**	**DOC 2005c**
		Vehicle inventory and use survey	**DOC 2005a**
		Revised construction industry energy use inventory	**Sharrard et al. 2007**
Global warming potential	**2002**	Revised 1996 IPCC guidelines for national greenhouse gas inventories	IPCC 1997
		Inventory of U.S. greenhouse gas emissions and sinks: 1990–2001	EPA 2006a
		Transportation Energy Data Book	Davis and Diegel 2005
Conventional air pollutants	1999	AirData	EPA 1999
	2002	National emissions inventory (NEI)	EPA 2005, 2006b
Toxic releases	2000	Toxic release inventory (TRI)	EPA 2002

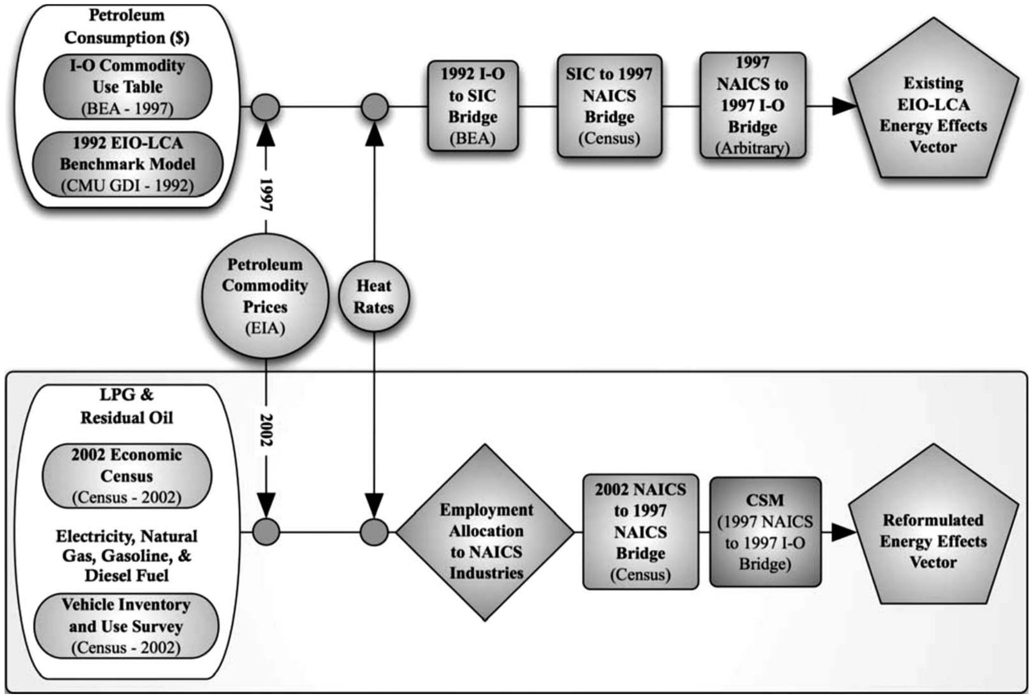

Fig. 1. Data source and process comparison for existing and reformulated energy effect vectors

require the user to create their own sector piecemeal (as with the current "custom" EIO-LCA feature). By providing supply chains for existing EIO-LCA sectors as starting points for custom products or processes, the chance that users will unintentionally omit integral aspects of economic interaction (and their resulting environmental effects) from their hybrid LCA is greatly reduced. Consequently, the EIO-LCA hybrid feature creates a system that has the benefit of EIO-LCA's large boundary while allowing for process-level user input that specializes the analysis.

As shown in Eq. (1), for normal I-O analyses such of those performed in EIO-LCA, the final demand (y) times the Leontief inverse matrix yields the total economic contribution from each sector; I=identity matrix and A=direct requirements matrix

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

However, with the I-O-based hybrid tool, once the user constructs a hybridized sector by using process-level data to alter A, the basic I-O calculation shifts to Eq. (2), which uses the revised direct supply chain ($A + \Delta A$) to determine direct and indirect economic and environmental effects

$$x = (I - (A + \Delta A))^{-1} y \tag{2}$$

For the I-O-based hybrid LCA model, the economic results from Eq. (2) are multiplied by the environmental vectors to yield environmental impact estimates for each I-O sector. Results are then presented to the user in the downloadable tabular form used for all EIO-LCA results; these results are sortable by category and comparable to nonhybridized EIO-LCA results. Given that both the EIO-LCA and hybrid tools are in the public domain, users can compare existing and hybrid EIO-LCA results for any sector. Currently, access to both the existing and reformulated effect vectors is only provided through the hybrid EIO-LCA feature. However, eventually the reformulated vector will become the de facto environmental effect vectors for the EIO-LCA construction sectors.

Construction Project Case Studies

To help determine the utility of the hybrid LCA model, eight case studies that could be used to model hybrid LCA functionality for an assortment of construction I-O sectors were compiled. These case studies, which are summarized in Table 1, included a residential home, a dormitory, several commercial office building iterations, roadway construction, bridge rehabilitation, and a neighborhood lighting maintenance and repair effort. Although only a small construction project sampling, the case studies demonstrate the benefits of modeling construction projects with the I-O-based hybrid LCA tool. The main requirement for case study data was that it had project information (i.e., year of construction, square footage, etc.) and an itemized budget. The itemized budgets facilitated case study data aggregation so it could be used as a process-level input for the I-O-based hybrid LCA model (which was ultimately used to edit the direct supply chain values for each respective construction sector). Because complete or nearly complete budgets were required, previously completed construction projects were preferable, but construction bids proved to be viable alternatives.

Ochoa Residential Case Study Results

By using a variety of case studies, the hybrid model's broad applicability was analyzed and confirmed. Of the case studies listed in Table 1, the "Ochoa Residential" and "Junnila/Guggemos U.S. Office Building" case studies were previously modeled by others, which allowed for comparison to past estimates of construction's environmental impacts (Junnila et al. 2006; Ochoa Franco 2004). All case study results were also compared to existing EIO-LCA estimations.

Specific results exist for each case study listed in Table 1, but only selected results are detailed here due to space considerations (Sharrard 2007). The original and hybridized Ochoa residential

Table 3. Itemized Direct Supply Chain Expenditures for Ochoa Residential Case Study [Original Data Extracted from Ochoa Franco (2004); Table Adapted from Sharrard and Matthews (2007a)]

I-O sector number	I-O sector description	Expenditures (1997$)	Factor difference between hybrid and original "D" values
212320	Sand, gravel, clay, and refractory mining	235	0.9
230110	New residential 1-unit structures, nonfarm	102,100	—[a]
314110	Carpet and rug mills	1,585	10.1
321113	Sawmills	9,146	6.9
32121A	Veneer and plywood manufacturing	4,019	4.5
321918	Other millwork, including flooring	4,339	7.2
32222A	Coated and laminated paper and packaging materials	342	0.9
324122	Asphalt shingle and coating materials manufacturing	341	2.2
325211	Plastics material and resin manufacturing	178	17.8
325212	Synthetic rubber manufacturing	440	331.3
325510	Paint and coating manufacturing	44	1.6
32619A	Plastics plumbing fixtures and all other plastics products	115	6.2
326192	Resilient floor covering manufacturing	469	0.1
327111	Vitreous china plumbing fixture manufacturing	81	0.2
32721A	Glass and glass products, except glass containers	376	1.3
327122	Ceramic wall and floor tile manufacturing	298	5.3
327320	Ready-mix concrete manufacturing	1,820	0.9
327420	Gypsum product manufacturing	2,162	4.7
327993	Mineral wool manufacturing	901	1.0
331111	Iron and steel mills	153	0.7
331112	Ferroalloy and related product manufacturing	31	—[b]
331421	Copper rolling, drawing, and extruding	35	0.8
331510	Ferrous metal foundries	61	0.2
332321	Metal window and door manufacturing	657	0.6
332322	Sheet metal work manufacturing	414	0.5
332500	Hardware manufacturing	289	0.6
332720	Turned product and screw, nut, and bolt manufacturing	84	1.6
332998	Enameled iron and metal sanitary ware manufacturing	1,216	7.4
333414	Heating equipment, except warm air furnaces	475	1.6
334512	Automatic environmental control manufacturing	111	1.6
335313	Switchgear and switchboard apparatus manufacturing	438	0.5
335930	Wiring device manufacturing	321	0.4
337110	Wood kitchen cabinet and countertop manufacturing	563	0.4
337212	Custom architectural woodwork and millwork	15,288	25.0
	Total	**150,673**	—

Note: Census=U.S. Census Bureau; and EIA=Energy Information Administration.

[a]Hybrid and original D values are the same.

[b]Original value was zero.

case study were previously published and the multiple stages required to rework the original Ochoa LCA into an I-O-based hybrid LCA were detailed (Ochoa et al. 2005; Sharrard and Matthews 2007a). This hypothetical 167 m^2 single-family residence cost $102,100 to construct in 1997 in Pittsburgh.

Table 3 summarizes the supply material and construction sector supply chain changes for the Ochoa residential case study, which were used in the I-O-based hybrid LCA model to yield final results. The Table 3 Ochoa residential supply chain values were analyzed using existing effect vector estimates and the reformulated vector estimates with both the existing EIO-LCA model and the I-O-based hybrid LCA tool (i.e., "EIO-LCA" and "Hybrid" in Fig. 2). Ochoa residential case study results for oxides of nitrogen (NO_x) and particulate matter with an aerodynamic diameter less than 10 μm (PM_{10}) emission estimates are provided in Fig. 2; these results are from running the final demand of $102,100 through the "new residential one-unit structures, nonfarm" I-O sector of the existing EIO-LCA model and the existing EIO-LCA model with the reformulated vectors (described previously). The "hybrid (reformulated)" values in Fig. 2 are the final estimates created by the I-O-based hybrid LCA tool. All other categories are only provided for comparison purposes.

Fig. 2 indicates that the NO_x estimates calculated with the reformulated effect vector are only 5% larger than NO_x emissions estimated with the existing EIO-LCA effect vectors. However, the much larger increase in NO_x estimates is attributable to the hybrid modeling. Overall, the reformulated hybrid LCA estimate for NO_x emissions from the Ochoa residential case study is 27% larger than the estimates from the existing EIO-LCA model; much of this change is attributable to the transportation sectors, as they provide the largest magnitude of NO_x emissions for the Ochoa residential case study.

As for PM_{10} emissions, Fig. 2 indicates that the reformulated vector is responsible for 55% of the nearly fivefold increase in

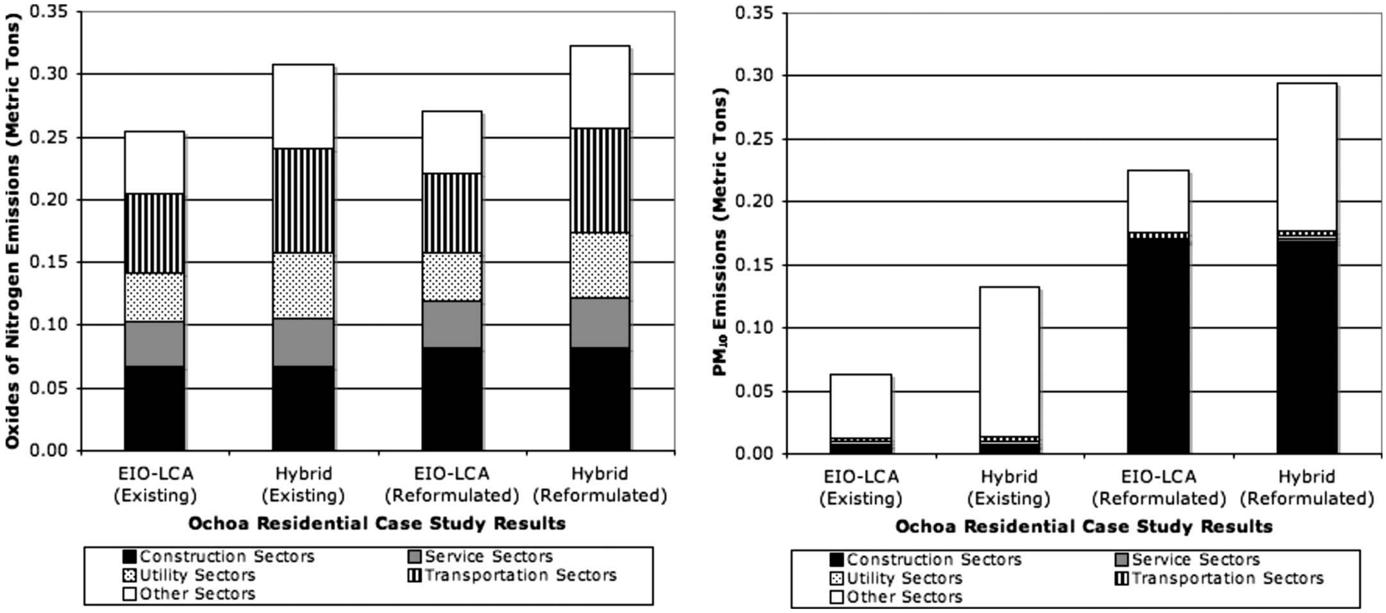

Fig. 2. Ochoa residential case study NO_x and PM_{10} I-O-based hybrid LCA model results

PM_{10} emissions, with hybrid modeling accountable for 45% of the increase. Within the reformulated effect vector additions to PM_{10} emissions, construction sectors are clearly the largest contributor. Results for the other EIO-LCA environmental effect categories are available, but not provided in this paper due to space limitations (Sharrard 2007).

Comparison of the Ochoa residential I-O-based hybrid LCA results to past LCA results is provided in Fig. 3 for energy use per square meter. Unless otherwise noted, the reference studies include impacts from construction and material life cycles. As Fig. 3 indicates, the Ochoa hybrid estimate of energy use in gigajoules per square meter (GJ/m^2) ranges between 1.3 times larger than the University of Southern Australia residences' energy use and 3.7 times larger than the Case 4 Norwegian row house (Pullen 2000; Winther and Hestnes 1996). All of these estimates are the same order of magnitude and most of these studies use either average national data (respective to their own countries) or extremely project-specific information in which construction is included, but not explained (Adalberth 1996; Pullen 2000; Ries 2000; Winther and Hestnes 1996). The fact that five of the studies in Fig. 3 are specific to other countries also contributes to the large result differences. In general, the construction and material energy use values were between 6 and 11% of the total residential life cycles analyzed (Adalberth 1996; Hellwig and Erhorn 1996; Lippke et al. 2004).

Fig. 3 also indicates that the hybrid Ochoa residential results are on par with the 2001 Keoleian standard home estimates (6.7 versus 6.6 GJ/m^2, respectively), though slightly smaller than the 2001 Keoleian energy efficient home estimate of 7.3 GJ/m^2 (Keoleian 2001). The Keoleian residential LCAs are mass based (ver-

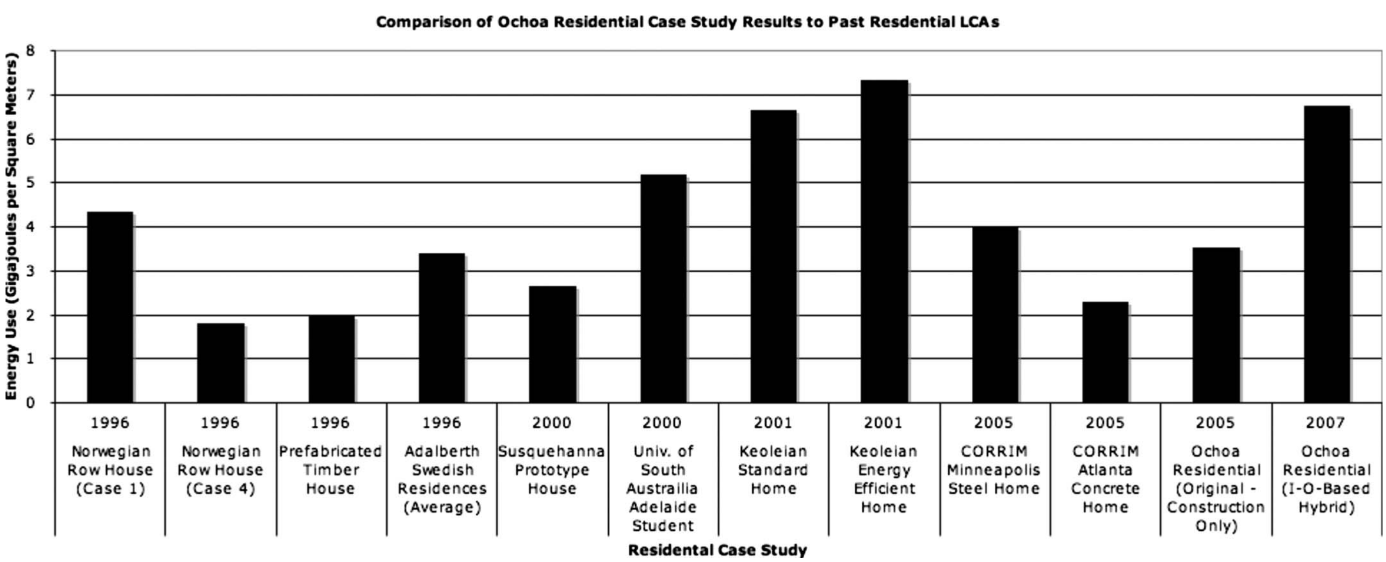

Fig. 3. Comparison of Ochoa energy use per square foot to past residential LCAs (Adalberth 1996; Hellwig and Erhorn 1996; Keoleian et al. 2001; Lippke et al. 2004; Ochoa Franco 2004; Perez-Garcia et al. 2005; Pullen 2000; Ries 2000; Winther and Hestnes 1996)

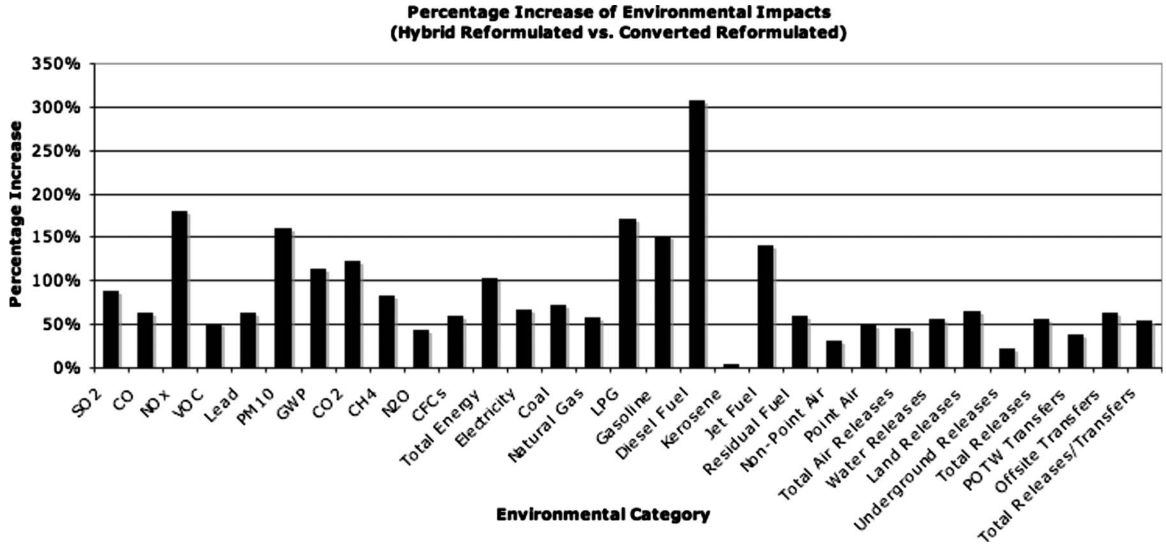

Fig. 4. Percentage increase in results by environmental category for Ochoa residential case study (hybrid versus converted original)

sus the dollar-based Ochoa residential case study), which is an alternative, and sometimes preferable way to model impacts. Given that both the Ochoa residential case study and Keoleian standard home are "standard," it makes sense that the energy efficient Keoleian home uses more material and construction energy than the other two because it requires more building materials, more unusual materials (which require more transportation), and more expensive materials—all things that increase mass- and dollar-based LCA analyses; Table 6 of Keoleian's analysis supports this conclusion (Keoleian 2001).

In general, Fig. 3 indicates that the Ochoa residential hybrid results are much larger than the original Ochoa case study results for energy use, *as well as* slightly larger than other past residential LCA results. As shown in Fig. 4, all environmental impact estimates for the Ochoa residential case study increased from the original Ochoa results (once converted to the 1997 EIO-LCA benchmark model), some dramatically so. The environmental impact categories shown in Fig. 4 are specific to EIO-LCA; for details about what each of these categories includes and their base units, please see CMU GDI (2007). In particular, estimates of total energy, gasoline, and diesel fuel use; particulate matter and nitrogen oxide emissions; and global warming potential more than doubled. Because these environmental impact estimates have increased so considerably, future building LCAs should also reveal parallel increases in fuel use and emissions.

Comparing Results for All Case Studies

Case study results can be compared to each other based on effects calculated from the reformulated effect vector, but also based on the environmental effects calculated using the original EIO-LCA effect vector. An example of this type of comparison is provided in Fig. 5, which illustrates that normalized NO_x emissions for each case study are all the same order of magnitude, but range within five times of each other. In general, all of the reformulated hybrid NO_x emission estimates in Fig. 5 are larger than the straight EIO-LCA results using both the existing and reformulated effect vectors. Reformulated hybrid results are 5–15% larger than

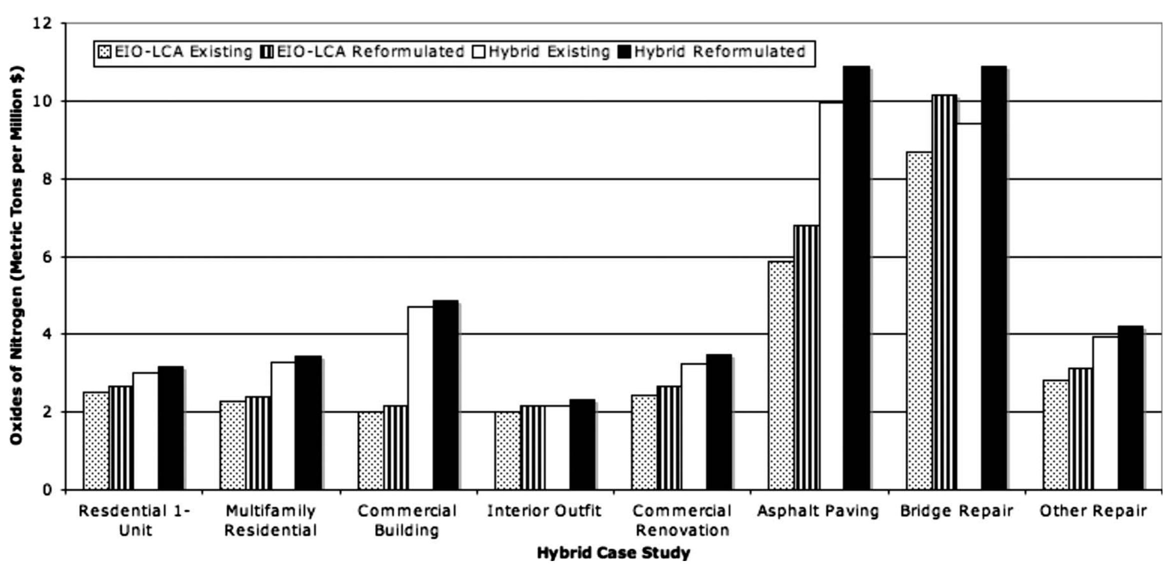

Fig. 5. Comparison of hybrid model NO_x results for existing EIO-LCA and reformulated environmental effects

hybrid estimates created using the existing EIO-LCA effect vectors. Normalized NO_x emissions from the asphalt and bridge repair case studies are approximately 3.5 times larger than the residential and commercial building case studies.

In general, both the data changes in the environmental effect vectors and data hybridization contributed to normalized NO_x emission increases, although hybridization's contribution is much larger for the commercial building and asphalt paving case studies. Figures such as Fig. 5 are also available for all other CAPs, energy use, GWP, and toxic releases (Sharrard 2007). Every case study also has specific graphs like Fig. 2 for each environmental category (Sharrard 2007).

Case Study Conclusion

All eight case study results indicate that the both the reformulated environmental effect vectors and the hybridization of sector supply chains using process-level data contributed to changes in the CAP emissions and energy use estimates, which generally increased, as many were more accurately captured and modeled in the reformulated environmental effect vectors. Specifically, PM_{10} emissions increased dramatically as a result of updating and reformulating the effect vectors, undoubtedly due to the inclusion of PM_{10} fugitive dust in the reformulation of effect vectors. CAP emission estimates for NO_x, carbon monoxide (CO), volatile organic compounds (VOCs), and sulfur dioxide (SO_2) also increased as a result of the effect vector reformulation, although the case study results generally indicate that data hybridization had a larger effect on CAP estimates than changes in the effect vector.

In terms of energy use, some total energy use estimations (and GWP, which is inherently linked to energy use) decreased as a result of the effect vector reformulation, although the majority increased. In general, hybridization was a much larger contributor to the overall increase in total energy and GWP estimates from the existing EIO-LCA model than changes in the effect vector. Specifically, electricity, natural gas, and liquefied petroleum gas result differences between the existing and reformulated effect vectors differed, with some sectors increasing, some decreasing, and others invariant. Residual fuel estimations had almost negligible changes as a result of reformulated effect vectors. However, case study results for the energy categories generally increased (often substantially) as a result of data hybridization.

Diesel fuel results were also mixed, with some estimates increasing and others decreasing due to the reformulated effect vector; hybridization's contribution to overall diesel use estimates also varied widely. Gasoline use estimates, on the other hand, increased 1.3–2 times that of the existing EIO-LCA results simply due to the reformulation of the effect vectors. Though not as much of an increase, data hybridization also substantially contributed to the overall increase in gasoline use estimates.

While this brief summary of case study results is an outcome of the I-O-based hybrid LCA model, it should be noted that all construction projects and case studies are different, so future results for other products and processes will generally be greater than existing EIO-LCA results, but the specifics and main sector contributions will vary. These differences simply reflect the inherent complexity and distinctive project nature of the construction industry.

Conclusion

This investigation provides background information on the construction industry and life-cycle assessment. It also discusses and illustrates the benefits of a hybrid LCA tool through description of an I-O-based hybrid LCA model that combines reformulated environmental effect vectors with the capability to edit the direct supply chain of EIO-LCA's sectors with process-level data. Eight construction case studies were modeled with the I-O-based hybrid LCA tool and, where possible, compared to past LCAs of construction projects.

Given that other studies have and continue to reference and apply EIO-LCA to construction-related analyses, it is important that EIO-LCA estimates of aggregate construction processes are accurate (Bilec et al. 2006; Guggemos and Horvath 2005; Junnila et al. 2006; Ochoa et al. 2005). The update and reformulation of the EIO-LCA construction sector environmental effect vectors is an alteration that will eventually become the de facto EIO-LCA effect environmental vectors, providing general EIO-LCA and construction industry stakeholders with a more up-to-date, complete, and documented allocation of national-level construction industry environmental data. Use of the full I-O-based hybrid LCA modeling tool will benefit life-cycle modeling researchers and construction industry stakeholders.

The main objective in using several case studies in the I-O-based hybrid model and comparing the results to other LCA frameworks where possible was to validate the I-O-based hybrid LCA model by determining the accuracy and comprehensiveness of its results versus the stand-alone process LCA and EIO-LCA models. One of the few published hybrid LCA construction case studies to date indicates that building material transport, equipment fuel combustion, and service sectors significantly contribute to a construction site's environmental footprint (Bilec et al. 2007). The analyses performed here for the I-O-based hybrid LCA indicate that the construction sectors themselves have an undeniably large contribution to the environmental effects of construction projects. Transportation and utility sectors also had increased roles for certain impact categories, while the service sector category designated for this research had a smaller effect than predicted, although service sector effects would be larger if the service sector boundary was expanded. A full list of the service sectors used for this research is available in the following reference; in general, it includes NAICS codes 541* and 561* (Sharrard 2007).

The work done in creating the I-O-based hybrid LCA model indirectly affects EIO-LCA results for the other 491 EIO-LCA sectors. Per the EIO-LCA direct matrix (D), the four maintenance and repair construction I-O sectors are the only construction sectors that appear in the supply chains of the other 491 EIO-LCA sectors. As some of the environmental effects of these four maintenance and repair sectors have increased substantially with the reformulation of the effect vectors (sometimes from a zero value), the impact of construction industry changes on nonconstruction EIO-LCA sector runs will be dependent upon how prominent the maintenance and repair I-O construction sectors are in other sectors' economic supply chains. With the current hybrid model and/or once the reformulated construction environmental effect vectors become the de facto EIO-LCA environmental effect vectors, EIO-LCA runs for nonconstruction sectors can quantify how past EIO-LCA analyses have underestimated the construction industry's environmental contributions to other industries. These types of analyses are part of future EIO-LCA and hybrid investigations.

The full I-O-based hybrid LCA tool, which is publicly available online at ⟨http://www.eiolca.net/aurora-hybrid.html⟩ (Sharrard and Matthews 2007b), goes beyond just a EIO-LCA data update and creates a mechanism for future hybrid analyses of construction projects (Sharrard and Matthews 2007b); additionally, this tool can be used with any of the 491 EIO-LCA sectors as a base sector, so a broad range of hybrid LCAs can be performed. Of course, the more accurate the process data used to inform these future hybrid LCAs, the better the results will be, but I-O-based hybrid analyses will exceed the accuracy of the general EIO-LCA model. Additional use of the I-O-based hybrid LCA tool beyond this research should be performed by a variety of stakeholders and decision makers, who can use the tool to model their own construction projects. Future research will also compare case study results from the I-O-based hybrid model to results from other extant construction hybrid LCA models from Bilec and Guggemos (Bilec 2007; Guggemos 2003).

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