LIFE CYCLE ANALYSIS OF THE DECONSTRUCTION OF MILITARY BARRACKS: FT. MCCLELLAN, ANNISTON, AL

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ABSTRACT

Nearly 2.5 million ft² of barracks must be removed from military facilities throughout the U.S. Environmental Protection Agency Region 4. While integration of manual deconstruction with traditional mechanical demolition methods has been shown to be comparable to traditional demolition methods in terms of cost and time requirements, the life cycle impacts of manual deconstruction on the environment and public health are unknown. To this end, life cycle assessment was applied to extend previous deconstruction studies of barracks at Ft. McClellan in Anniston, Alabama. Four scenarios were compared with varying degrees of time required for manual deconstruction of the barracks—100% Manual, 44% Manual, 26% Manual, and 100% Mechanical. Data were collected directly from the site and applied using SimaPro modeling software (Pré Associates, The Netherlands), considering two post-deconstruction options. Materials salvaged using either 100% or 44% Manual deconstruction and reused within a 20-mile radius of the deconstruction site yielded the most favorable environmental and health impacts. The significant impacts involved in the life cycle of diesel fuel required for transportation emphasize the need for developing reuse strategies for deconstructed materials at the regional level.

KEYWORDS

life cycle assessment, deconstruction, demolition, salvage

INTRODUCTION

Each year, the building industry in the United States is reported to generate nearly 136 million tons of construction and demolition (C&D) waste, amounting to 35–40 percent of the total amount of municipal solid waste (MSW) produced annually (Dolan et al. 1999). Approximately 60 percent of this C&D waste originates from the demolition of buildings, and 80-90 percent is estimated to be either reusable or recyclable (McPhee 2002). While reuse and recycle of C&D-related waste offers potential environmental advantages, the building and deconstruction industry has not fully embraced these practices (Lippiatt 1998).

There are two different methods for the removal of buildings—deconstruction and demolition—and the method used greatly influences the amount of salvaged (reusable) material gained. Demolition, the common means of building removal, is equipment-intensive, requiring machinery throughout the process for leveling the building and separating the larger materials (Falk and Lantz 1996). Deconstruction involves the methodical disassembly of buildings in order to reuse or recycle as many of the component parts of the building as possible, before or instead of demolition (Falk and Lantz 1996, McPhee 2002). Deconstruction has been perceived to be a solution to the problems resulting from increasing demands of virgin building materials, the associated emissions from the various life cycle stages of virgin material preparation and use, and increased burden of landfills as buildings age. However, the additional time burden and perception of associated increased costs accompanying deconstruction have hampered its practice. Supplementary planning is also required in deconstruction compared to demolition in order to assess the type and amount of materials that can potentially be salvaged. The actual deconstruction phase must involve greater oversight of labor, while recovered materials must be stored and protected on

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site before removal to their final destination. In addition, most of the salvaged lumber can be used only for non-structural applications, such as in decks and non-supporting walls, unless the materials are regraded (Falk et al. 1999). In order to minimize the time and cost burdens of deconstruction, while still ensuring gain of salvaged materials, this practice can be combined with demolition.

A recent study reported results of an effort conducted at Ft. McClellan in Anniston, AL, where four World War II-era military barracks were subjected to hand deconstruction, combined hand-mechanical deconstruction methods, and traditional demolition, with the primary goal of determining the "optimal" deconstruction method based on salvage value per unit of cost (Guy 2006a, 2006b). The deconstruction at Ft. McClellan was funded by the U.S. Department of Defense (DOD), which is charged with removing over 2,357,094 square feet of excess buildings from military bases throughout U.S. Environmental Protection Agency (U.S. EPA) Region 4 alone (Falk et al. 1999). Primary drivers for the removal of these buildings via deconstruction and salvaging are a combined federal procurement law (CFR 32 162.2) that will not allow federal tax dollars to be spent on the maintenance of facilities that are in surplus of needs (Falk et al. 1999, CFR 2004), waste minimization goals set by the U.S. Army, and a desire to subsidize the overall disposal costs of the buildings with salvaged materials, thus lowering funding requirements (Falk et al. 1999). Guy (2006a, 2006b) included four scenarios representing four different methods of removing the Ft. McClellan barracks. Scenarios 1 and 4 involved 100% manual and mechanical methods, respectively, whereas Scenarios 2 and 3 involved an increasing ratio of mechanical/manual methods. Guy (2006a) concluded that Scenario 3 was the "optimal" method, yielding a 32% salvage weight that was, however, accompanied by a 10-fold increase in labor-hours, 40.5% greater gross costs, and 9% greater net costs in comparison to Scenario 4. The study's conclusion that large environmental savings would result from the increased salvaging from Scenarios 1–3 is based solely on diversion of the salvaged materials from the landfill. The life cycle environmental benefits of manual deconstruction in comparison to mechanical demolition are not as clear, given the increased labor force demands and concomitant energy requirements involved in manual deconstruction.

This paper describes work, also funded by the U.S. DOD, extending the studies of Guy (2006a, 2006b) by determining the relative environmental and health impacts of manual deconstruction and mechanical demolition of pre-World War II barracks using a life cycle approach. Life cycle assessment (LCA) is a method that enables quantification of the environmental and public health impacts of an activity or product throughout its entire life. This "cradle-to-grave" approach is based on the knowledge that each stage in a product's life has potential to contribute to its environmental impacts. Considering a building's life cycle, these stages include raw material extraction and processing, material manufacture (e.g., wood harvesting and milling), transportation, installation (e.g., construction), operation and maintenance, and, ultimately, recycling and waste management (e.g., salvaging of materials for recycling or reuse) (Lippiatt 1998). A life cycle model describing the deconstruction and demolition processes used at Ft. McClellan and the specific emissions and resulting environmental impacts are compared using LCA methods and are reported herein.

METHODS

The Deconstruction Process and Four Scenarios Studied

The deconstruction and demolition of four barracks were conducted from April-June of 2003. Personnel involved in this project participated in either a deconstruction team or an LCA team. The deconstruction team was responsible for hiring a dismantling contractor, coordinating the dismantling of each barrack in a systematic approach, and collecting data during the deconstruction process, as described in detail by Guy (2006a). With the aid of Costello Dismantling Co., Inc. (Boston, MA, USA), contracted in the early stages of the project, the deconstruction team carefully documented in 15-minute intervals at the deconstruction site the following information: type and amount of material salvaged or disposed, method of material removal (manual or mechanical), time required to salvage and/or demolish, time required for machine operation, total labor time and transportation requirements, as previously described in detail (Guy and Williams 2004, Guy 2006a, 2006b). The LCA team transferred the data collected from the site and applied these data to the modeling efforts.

As stated previously, the primary goal of this study was to assess the optimum combination of manual and mechanical methods of barracks removal, as measured by minimum environmental/public health life cycle impacts. The four scenarios studied in Guy (2006a, 2006b) were re-labeled here as 100% Manual and 100% Mechanical (referring to Guy's Scenarios 1 and 4) and 44% Manual and 26% Manual (referring to Guy's Scenarios 2 and 3) to more clearly reflect the degree of manual and mechanical activity. These percentages refer to the time used for mechanical demolition or manual deconstruction and were determined by dividing the total labor-hours required for building removal into the total time required for machine operation or hand laborer.

Life Cycle Assessment

All data collected from the deconstruction phase were carefully databased for use in the LCA modeling that followed ISO 14000 guidelines (Guinée et. al. 2002). The ultimate objective of the LCA effort was to guide the Department of Defense (DOD) in the best management practices for removing the WWII-era barracks that remain in U.S. EPA Region 4 with the least environmental damage. The scenario yielding lowest environmental impacts would be considered the most preferable option in this study. The development of the LCA model and its relevant stages are discussed in more detail below.

Functional Unit. The four scenarios were compared on the basis of inputs, outputs, and the resulting impacts using a functional unit of "per square foot of barracks." All results presented herein are based on this functional unit.

Scope and Goal Definition. The relevant stages included in this LCA are the deconstruction/demolition process, representing "raw material extraction"; disposal of materials by landfilling; transportation between the stages; and recycling and reuse of salvaged materials by replacing virgin materials. Figure 1 shows these stages divided into individual steps, starting with preparation for deconstruction by transportation of equipment and labor to the site and removing asbestos (Steps 1a and 1) and hazardous waste (Step 2). Each rectangle (Steps 1, 2, 5, 13–16) represents an activity that is involved in preparation for demolition of the barracks, preparation of salvaged materials for reuse, and the processes in the outer avoided virgin wood production loop. Each oval (Steps 3, 4, 6–12) represents a part of the barrack disposed of in the landfill or salvaged for reuse. Time requirements for each relevant step under each scenario were collected at the site for subsequent LCA development. The only steps shown in Figure 1 relevant to the 100% Mechanical scenario are transportation of labor and equipment to the site, asbestos and hazardous waste removal and transportation to disposal sites (Steps 1, 1a, 1b, 2 and 2a), whereas all subsequent steps apply to only the other three scenarios.

In this LCA, two cases were considered for material salvaged in the four scenarios. The first case, involving salvaging of materials and their subsequent reuse within 20 miles of the deconstruction site, was performed from the perspective of savings in landfill volume requirements and reduction of resulting leachate. By considering nearby reuse and recycle applications for the salvaged material, this case provides a measure of the impacts of a regional market for these materials. The second case involved reuse and recycle of the salvaged materials beyond the 20-mile radius from deconstruction and landfill sites by incorporating transportation to the Habitat for Humanity (HfH) warehouse in Austin, TX, thus assessing impacts of a national market for these materials. HfH was used as hypothetical end market for the salvaged materials because of the interest expressed by this organization in the deconstruction project at Ft. McClellan and because of the readily available facility space in its Austin reuse center. For both the second and third cases, if use of the salvaged material avoided the production and preparation of the virgin wood that it replaced, then the avoided virgin wood production loop (Steps 13a-16) and the recycling of MEP materials (Step 5a) were involved.

Data Inventory. Both primary (derived directly from the deconstructed and demolished barracks) and secondary (derived from literature and regulatory agency publications and databases) data were

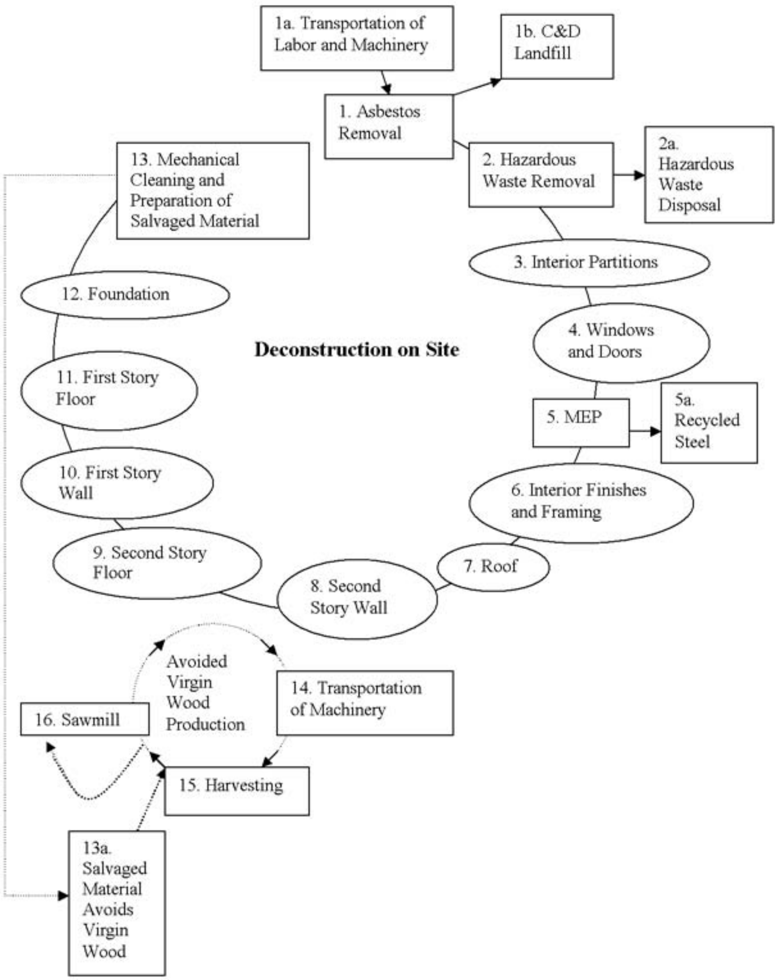


FIGURE 1. Stages involved in the deconstruction process.

collected and databased in LCA software, SimaPro 5.1 (PRé Consultants, Ameersfort, The Netherlands). SimaPro contains inventory data that has already been gathered for common products and processes in databases created by ETH-ESU (Uster, Switzerland), Buwal 250 (Bern, Switzerland), and Franklin Associates (Prairie Village, Kansas, USA), among others (Goedkoop and Oele 2001). As previously described, the primary data collected included the amounts of hazardous, salvaged, recycled and landfilled materials, the amount of time each piece of equipment was used, the number of workers, and the worker labor time (Guy 2006). In addition, the weights of salvaged and landfilled materials were found by weighing the hauling trucks before and after delivery of the waste. The weights of the salvaged materials and all building materials were found by using a scale located on the site. Weights of all representative materials were measured by weighing a sample of known size and then extrapolating to a unit of standard measurement depending on the material type, such as linear feet for wood (width x thickness) or square feet of sheet materials of known thickness. The secondary data included types of equipment and materials used (site-specific for project), fuel type and requirements of each piece of equipment (JLG 2004, Bobcat 2004, Caterpillar 2004, Grove 2004, Homelite 2004, Stihl 2004, DeWalt 2004), amount and composition of leachate from all deconstruction materials (Jamback 2004), equipment usage for production of virgin wood in the forest and at the sawmill (Long 2003), emissions from production of bricks used in the barracks construction (U.S. EPA 1997), recycling and producing steel (U.S. EPA 1986), production and combustion of diesel and gasoline (U.S. EPA 1995), and production of electricity using the U.S. electricity mix (SimaPro 5.1). The LCA compared the inputs and outputs of each alternative scenario in terms of emissions, the value of the material, and requirements of dollars, energy, and labor.

Impact Assessment. While a number of weightings schema used in LCA impact assessment have been developed and are available to LCA practitioners, the need for an increased understanding of how these metrics are developed, their uncertainty and variability, and potential limitations and benefits of their application has been recently identified (Thomas et al. 2003). The SimaPro 5.1 version of the software used in this study provided a number of choices for impact assessment approaches. In this study, two methods, the Centrum Voor Milieukunde Leiden (CML) 2000 and Environmental Design of Industrial Products (EDIP), were chosen for calculation of the relative impacts of Global Warming, Ozone Depletion, Acidification, Eutrophication, Human Toxicity, and Ecotoxicity (Guinée and Heijungs 1993; Goedkoop et al. 1998; Goedkoop and Spriensma 1999; CML 2001; Goedkoop et al. 2003). These two approaches were chosen from those available in the SimaPro 5.1 software because they are commonly used in LCA impact assessments and take different approaches for calculating impacts, while considering similar contributing factors for each impact. Comparing the results of these two approaches enables determination of the reliability of the observed trends. A detailed description of these methods can be obtained in Sivaraman and Lindner (2004), and currently available approaches included in the latest version of SimaPro can be studied in more detail directly on the PRé Consultants web site (http://www.pre.nl).

Assumptions and Limitations

The following is a list of assumptions made throughout this assessment to enable comparison of the four scenarios:

1. Each barrack contains the same quantity of hazardous material, asbestos, and wood coated with lead-based paint that must be disposed; therefore, these emissions were not accounted for in the LCA.
2. Transportation: Note that all assumptions of distances traveled were considered for their effect on the results in the sensitivity analysis.
   - The workers made a 20-mile roundtrip to and from work each day in a 1995 model midsize car. Each worker drove his/her own car; however, carpooling was considered for its effect on the results in the sensitivity analysis. A 20-mile distance served as a worst-case scenario because this represents approximately twice the distance most workers travel to work (Khattak et. al. 2005, Demographia 2005).
   - Equipment was transported to the site on a flat bed truck from within a 20-mile radius. Because this distance varies for every site, the variable of transport distance was included in the sensitivity analysis.
   - A 30-mile distance for transport of equipment to and from the site of harvesting was assumed (Long 2003), and harvested wood was assumed to be transported 60 miles to the sawmill (Long 2003). A transport distance of finished lumber of 100 miles was assumed from the sawmill to the construction site for virgin wood (Long 2003).
3. Except for small equipment (chainsaws, chopsaws, and weedeaters), each piece of equipment used at the barracks site required a separate flat bed truck for hauling.
4. The capacity of each truck hauling harvested wood was at least capable of handling 5,500 lbs of wood, equal to a cord of wood.
5. Other than the use stage, the life cycle stages of the machinery used throughout the deconstruction or demolition process were not considered.
6. Sources of emissions included from the creation of virgin timber were harvesting, transporting the wood, milling the wood, and transporting the lumber to the construction site.
7. The data collected at the barracks in Ft. McClellan are applicable to all other barracks within U.S. EPA Region 4.
8. Methods for asbestos abatement and lead assessment are the same whether for demolition or deconstruction.

9. The wood deposited into the landfill was untreated chemically, but most of it was painted with lead-based paint. Wood coated with lead-based paint produces lead-contaminated leachate; however; the effects of this wood were not accounted for in the leachate because there was the same amount in each barrack. Because the landfill is unlined, the leachate from all other materials contained within the barracks was accounted for using data reported in Jamback and Townsend (2004), the only available resource for this type of data.
10. The source of electricity was assumed to be the average U.S. mixture of 56% coal, 21% nuclear, 10% hydropower, 10% natural gas, and 3% crude oil. The safety concerns of spent nuclear fuel were not considered.

Sensitivity Analysis

Assumptions and variables that were tested for their sensitivity to model results included the effect of salvaging, distances the workers traveled, the distances the materials and machinery were transported, the recycling of the steel, and the time requirements for preparation of the materials for reuse.

RESULTS AND DISCUSSION

Data Inventory

Time Requirements for Removal of Barracks Components. As shown in Table 1, each barrack component was partitioned into broad categories of windows and doors, interior partitions, hazardous waste (composed primarily of mercury thermostat switches, lead-acid batteries in exit lights and emergency light fixtures, fluorescent tubes and ballasts), mechanical, electrical and plumbing (MEP) materials (including sinks, toilets, showers, light fixtures, wiring and conduit, ducts, and air handlers), interior finishes and framing, roof, walls and floors, and foundation. Each of these components is described in detail by Guy (2006a). The time required to remove each building component following the relevant set of steps conducted in each scenario is also provided in Table 1. Asterisks in Table 1 denote all components that were removed with some degree of mechanical methods.

TABLE 1. Time requirements for removing components of barracks using the four scenarios varying in degree of manual deconstruction[a, b]

	100% Manual		44% Manual		26% Manual		100% Mechanical	
Component	Time (hours)	% Total Time	Time (hours)	% Total Time	Time (hours)	% Total Time	Time (hours)	% Total Time
Windows and Doors	9.57	1.46%	9.57	2.01%	9.57	2.64%	0.00	0.00%
Interior Partitions	18.97	2.90%	18.97	3.99%	18.97	5.24%	3.09*	8.81%
Hazardous	5.05	0.77%	5.05	1.06%	5.05	1.39%	5.05	14.39%
MEP	9.54	1.46%	9.54	2.01%	9.54	2.63%	1.03*	2.94%
Interior Finishes and Framing	73.55	11.23%	73.55	15.48%	50	13.81%	3.09*	8.81%
Roof	137.15	20.94%	95*	19.99%	77*	21.26%	6.18*	17.61%
2Wall	52.75	8.05%	45.28	9.53%	29.12*	8.04%	2.06*	5.87%
2Floor	147.69	22.55%	71.92*	15.13%	84.4*	23.31%	5.15*	14.68%
1Wall	64.30	9.82%	62.27	13.10%	9.29*	2.57%	2.06*	5.87%
1Floor	133.07	20.32%	80.84*	17.01%	65.9*	18.20%	4.12*	11.74%
Foundation	3.26*	0.50%	3.26*	0.69%	3.26*	0.90%	3.26*	9.29%

[a]All of the sections of the barrack within which machines were used are indicated with an asterisk (*), and all sections that do not have an asterisk next to them used hand deconstruction only.
[b]MEP = Mechanical, electrical and plumbing materials, 2Wall = Second story wall, 2Floor = Second story floor, 1Wall = First-story wall, 1Floor = First-story floor.

Removal of hazardous materials (fluorescent lights and exit signs) and the foundation of each of the barracks, mechanically performed in all scenarios, required the same amount of time (5.05 and 3.26 hrs, respectively). Removal of windows and doors, interior partitions, and MEP materials required the same amount of time for the three scenarios that involved hand deconstruction (100% Manual, 44% Manual, and 26% Manual) but a significantly lower time for the 100% Mechanical scenario. The windows and door frames coated with lead-based paint and the MEP materials were manually removed from the barracks involving hand deconstruction. The wood with lead-based paint was not considered hazardous waste because of the low concentrations of the paint, and, therefore, it was disposed of in a C&D landfill. The windows and door frames from the 100% mechanically demolished barrack were disposed of thus yielding no time requirement, whereas the time for removing MEP materials under this scenario was lower than the other three because only the light fixtures, electrical wiring and conduits were removed before the demolition of the building. The 3.09 hours required to remove interior partitions from the 100% mechanically demolished barrack involved recovery of the large support columns only. The same amount of time was needed for the salvaging of the interior finishes and framing for the 100% Manual and the 44% Manual scenarios, but a decreased amount of time was needed in the 26% Manual scenario. This decreased time is explained by the fact that the columns and wall studs were cut using chainsaws to speed the process of deconstruction and so that the second story floor could be dropped onto the first story floor for deconstruction.

As shown in Table 1, regardless of the scenario, the greatest percentage of time was required to remove the roof and second-story and first-story floors. With the exception of the removal of the second-story floor, less time was required for removal of the roof, walls and floors of the barracks with increasing percentage of mechanical methods used. The removal of the second-story floor using the 26% Manual methods, involving dropping the floor onto the first-story floor before dismantling, required approximately 84 hours for removal, whereas the 44% Manual scenario, involving cutting the floor first into ten-by-ten foot pieces and dismantling these on the ground, required approximately 72 hours for this task. The time for the removal of the first-story wall also varied greatly between the 44% Manual and 26% Manual scenarios. The former, involving manual removal of sheathing and siding, required approximately 62 hours, and the latter, involving cutting at the floor base and direct disposal in a dumpster for ultimate landfilling, required approximately 9 hours. For more information on the methods used to deconstruct and demolish the barracks and the time differences for the removal of the different components of the building, please refer to Guy and Williams (2004) and Guy (2006a, 2006b).

Labor and Machine Time and Mileage Requirements and Material Yields. Table 2 presents the total labor and machine time and transportation requirements for the material yields from each of the four scenarios. As expected, the scenario involving all manual deconstruction demanded the greatest number of work days and mileage requirements of the work crew, 13.62 days and 1634 miles, respectively,

TABLE 2. Labor and machine requirements and material yields of the four scenarios studied

	Labor and Machine Requirements				Material Yields			
Scenario	Labor (days)	Machine (hours)	Labor Transportation (miles)	Equipment Transportation (miles)	Salvage Weight (lbs)	Recycle Weight (lbs)	Hazardous Material Weight (lbs)	Landfilled Weight (lbs)
100% Manual	13.62	80.22	1634	120	59089	1032	141	82486
44% Manual	9.87	286.77	1184	140	57291	1032	141	84284
26% Manual	7.54	245.16	904	120	48134	1032	141	93441
100% Mechanical	1.46	23.42	88	40	2552	0	141	140055

compared to the range of 9.87 to 1.46 days and 1184 to 88 miles for the other scenarios, decreasing with less manual deconstruction. Interestingly, the time requirement for machine operation and mileage requirements for delivery of machinery were maximum in the 44% Manual scenario (286.77 hrs, 140 miles, respectively) because an additional piece of equipment, a crane, was used in this scenario to lift the roof off the building so that the salvageable pieces of the roof could be saved while the rest of the building was demolished. It is important to note that machines were necessary in the 100% Manual scenario for collection, movement and cleaning of materials.

The 100% mechanical demolition scenario required the least amount of transport mileage of equipment and machine hours because only two pieces of equipment were involved, the Bobcat T200 Turbo (Bobcat, West Fargo, ND) and Caterpillar 320C excavator (Caterpillar, Inc. Pleasanton, CA), to simply topple the building with no manual removal processes. Also, unlike the three scenarios with manual involvement (during which materials were separated and moved to various locations on site), the 100% Mechanical scenario resulted in materials transferred directly to an on-site dumpster for subsequent disposal.

The amount of recycled material was the same for each barrack that used hand deconstruction (Table 2). In 100% mechanical demolition, the building was knocked down and put in the C&D landfill without removing the recyclable steel. As anticipated, the yield of salvageable material decreased with diminishing levels of manual labor. The weight of salvaged material ranged from 2,552 lbs from the barrack that was entirely mechanically deconstructed to 59,089 lbs from the entirely manually deconstructed barrack. The barrack that was mechanically deconstructed yielded salvaged material in the form of large wood columns, the foundation of the building, and plumbing and electrical fixtures. Additional components salvaged with manual methods included non-damaged wood, showers, urinals, toilets, air conditioning ducts, and some of the bricks from the chimney (if clean of mortar).

The amount of hazardous material (141 lbs) was the same for each barrack, as each barrack contained the same items with hazardous components, including mercury thermostat switches, lead-acid batteries in exit lights and emergency light fixtures, and fluorescent tubes and ballasts. As salvaged material yields increased, the amount of material sent to the landfill decreased. Therefore, as also anticipated, the amount of landfilled material decreased with increasing manual labor rates. The amount of material landfilled ranged from 140,055 lbs for 100% mechanical demolition to 82,486 lbs for 100% manual deconstruction.

Fuel and Electricity Requirements. The hourly fuel and electricity requirements for transportation of the labor force and machinery and for the operation of each of the machines are provided in Table 3, along with the relevant stages of their involvement, previously introduced in Figure 1. Seven different pieces of machinery that were used during the deconstruction and demolition of the military barracks are also listed in Table 3. Each of these pieces of equipment was used for a different purpose and for varying amounts of time depending on the scenario. The JLG Lift 600S (JLG Industries, Inc., McConnellsburg, PA) was used to raise the workers above the roof in order to cut and remove panelized sections in the 100% Manual and 26% Manual scenarios. The Bobcat T200 Turbo was used to move the loose salvaged material and floor panels to the designated places for pick up and disposal in all four scenarios. The Caterpillar 320C excavator was used to knock down the 100% mechanically demolished building and to push over the building in the 26% Manual scenario. In all the other scenarios, the Caterpillar excavator was used to pick up the floor panels from the second floor and flip over the first floor panels. The Grove TMS 760E crane (Grove, Pensacola, FL) was used for the removal of the roof in the 44% Manual scenario. The Homelite Chainsaw (Homelite, Port Chester, NY) and Stihl Chopsaw (Stihl Inc., Jacksonville, FL) were used to cut the roof into panelized sections either on the ground or in the air with the help of the JLG Lift 600S. The chopsaw was also used to cut the first and second floor panels in the Manual scenarios. The chainsaw was used to cut the roof rafter for roof panelizations, the second floor joists and beams for panelization, and the columns and wall studs in the 26% Manual scenario so that the second floor could be dropped onto the first floor and dismantled there. The DeWalt DG7000E generator (DeWalt Industrial Tool Company, Baltimore, MD) was used to remove nails and paint from the salvaged wood with attached tools in all four scenarios.

The 100% Manual scenario required operation of the lift, bobcat, excavator and chopsaw for 4, 4, 0.5 and 3 total hours, respectively (data not shown). The same equipment was used in the 26% Manual scenario, requiring increased times for use of the lift, bobcat, excavator and chopsaw of 5, 1, 6 and 7 hours, respectively. In the 44% Manual scenario, the lift, bobcat, and excavator were also used in addition to the chainsaw and crane (for a total of 6, 9.5, 1, 3, and 4.5 hours, respectively). Only the bobcat and excavator were required in the 100% Mechanical scenario, each used for 2 hours total. As shown in Table 3, the chopsaw, chainsaw, and generator required gasoline (0.20, 0.12, and 0.63 gallons/hr, respectively) (Stihl 2004, Homelite 2004, DeWalt 2004), whereas the other equipment required diesel fuel in larger volumes (ranging from 2.50 to 8.10 gallons/hr) (Bobcat 2004, Caterpillar 2004, Grove 2004, JLG 2004).

The fuel and electricity requirements for harvesting and processing virgin wood are also provided in Table 3. The primary equipment pieces involved in harvesting of wood are feller bunchers, rubber- tired skidders, and log loaders. The requirement of 29 gallons of diesel fuel used during the transportation of this equipment to and from the forest was overwhelmingly greater than in-use fuel consumption. In fact, the consumption during transportation of the equipment to the forest for harvesting was greater than any of the other diesel fuel consumption requirements incurred during transportation, including transport of the downed trees to the sawmill, of the lumber to the construction site, of the recycled steel to the recycling facility, and of the waste materials to the landfill. Electricity requirements for sawmill operation (6.2E-03 kWh per pound of wood) and recycling of steel (2.1 kWh per pound of recycled steel) were also accounted for, as shown in Table 3. It is important to note that, for every pound of salvaged wood, one pound of processed virgin wood was avoided. Thus, the values provided in Table 3 represent "savings" in relation to using all virgin materials in reconstruction applications, and their resulting emissions will be considered as "emissions savings" rather than contributions.

Emissions. Tables 4, 5, 6 and 7 show the primary environmental emissions that result from each of the four scenarios per square foot of barrack. The emissions shown in these tables represent the first case where material salvaged is reused or recycled within 20 miles of the deconstruction site. Emissions from the other case—transportation of all reusable materials to Austin, TX—are considered in the discussion of impact assessment results below. While the SimaPro 5.1 modeling software included hundreds of emissions from the included life cycle stages, only those in highest quantity and/or risk to the public and environment were considered. These emissions have been broken down into four categories—criteria pollutants, greenhouse gases, metals, and miscellaneous chemicals—which have been further separated by life cycle stage, during salvaging of material (Stage 13 in Figure 1), disposal (Stages 1b, 2a and the waste from stages 3–12), use of equipment during deconstruction (Stages 3, 4 and 6–12), and transport of equipment and labor to and from the site (Stage 1a). The emissions with negative values in Tables 4, 5, 6, and 7 represent savings as a result of replacing virgin materials with salvaged materials.

The most highly emitted species from all four scenarios were carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), nitrogen oxides (NO_x), and methane (CH_4). The remaining chemical emissions, dioxin, arsenic, lead, and mercury, are listed in the tables because of their known toxicity. Total CO_2 and CH_4 emissions increased and VOC and CO emissions decreased with decreasing degree of manual involvement. Despite small increases in emissions of CO from the disposal stages from the 100% Manual to the 100% Mechanical scenario, the decrease in CO and VOC emissions from equipment (resulting from decreasing use of the generator used to clean salvaged materials) and transportation (resulting from the decreasing transportation mileage from the commute to/from the site by the labor) overwhelmingly influence the total CO and VOC values. As expected, the C&D landfill contributed the largest emissions of CO_2 and CH_4 regardless of the scenario, and the increases in materials disposed of in the landfill resulted in an increase in these emissions with decreasing degree of manual involvement. Also, emissions of arsenic, lead, and mercury in leachate from the landfill increased as manual involvement in deconstruction decreased, thus yielding a lower amount of materials that are

TABLE 3. Fuel and electricity requirements for associated processes[a,b]

Processes	Involved Stages[c]	Gasoline (gal)	Diesel Fuel (gal)	Electricity (kWh)
Labor				
Transportation (1 laborer, 1 day of work)	—	8.0E-01	—	—
Deconstruction				
Transportation To and From the Site	—	—	6.4E+00	—
Lift (hr)	7, 8	—	2.5E+00	—
Bobcat (hr)	6, 7, 9, 10, 11, 12	—	5.0E+00	—
Excavator (hr)	7, 12	—	8.1E+00	—
Crane (hr)	7	—	4.0E+00	—
Chopsaw (hr)	7, 11	2.0E-01	—	—
Chainsaw (hr)	7, 8, 9, 10, 11	1.2E-01	—	—
Generator (hr)	13	6.3E-01	—	—
End-of-Life Stages				
Salvaging Wood (1 lb)				
Harvesting				
Transportation of Equipment to and from the Forest	14	—	2.9E+01	—
Feller Buncher (1 lb)	15	—	1.7E-03	—
Rubber Tired Skidder (1 lb)	15	—	2.8E-03	—
Log Loader (1 lb)	15	—	3.1E-03	—
Transport from Site to Sawmill (1 lb)	15	—	9.0E-03	—
Sawmill				
Electricity (1 lb)	16	—	—	6.2E-03
Transportation from the Sawmill to Construction the Site (1 lb)	16	—	3.0E-03	—
Recycling Steel (1 lb)				
Electricity (1 lb)	5a	—	—	2.1E+00
Transportation to Recycling Facility	5a	—	1.6E-02	—
Landfill (1 lb)				
Transportation to Landfill	1b	—	1.6E-02	—

[a]Values of fuel requirements by the equipment are presented on an hourly basis, and values of electricity are presented per pound of salvaged or recycled material.
[b]All fuel usage values were obtained by contacting the manufacturers of the machines and asking for average fuel usage values.
[c]Stage numbers refer to the specific stages involved and shown in Figure 2.
[d]Mileage workers drove to/from the site was assumed to be 20 miles, equipment transported from within a 20 mile radius to site, 30 miles to/from the forest, 60 mile transport for harvested wood to sawmill, 100 mile transport from sawmill to construction site and an 80 mile transport distance for salvaged material to new construction site.

landfilled. These metals in particular leach from the wood and the joists (Tables 4–7).

Total emissions of NO_x are highest in the 100% Mechanical scenario (87.7 g/ft^2 barrack, Table 7) and lowest in the 44% Manual scenario (46.9 g/ft^2 barrack, Table 5), with total emissions from the 100% Manual and 26% Manual scenarios (74.6 and 49.6 g/ft^2) falling in between these values. The lower emissions of NO_x with a decrease in manual involvement in the manual deconstruction scenarios can be explained by the decreased use of cars for transportation of workers. The number of days the workers

TABLE 4. Emissions from the scenario involving 100% manual methods[a]

Emission	Total	Salvaged Material	Disposal	Recycled Material	Equipment[b]	Transportation[c]
Criteria Pollutants						
Carbon Monoxide (CO)	3.52E+03	-8.29E+01	6.94E+01	9.36E-01	1.94E+03	1.59E+03
Nitrogen Oxides (NO_x)	7.46E+01	-7.06E+01	4.79E+01	-9.59E-01	5.55E+01	4.28E+01
Air Toxics						
Dioxin	-8.16E-12	-2.76E-11	1.50E-11	1.87E-13	3.17E-12	1.08E-12
Greenhouse Gases						
Methane (CH_4)	8.49E-01	-2.29E+00	2.43E+00	3.03E-02	5.09E-01	1.70E-01
Carbon Dioxide (CO_2)	3.35E+02	-1.46E+03	1.57E+03	-2.72E+02	3.86E+02	1.11E+02
Metals						
Arsenic (As)	5.77E-05	-1.50E-04	1.93E-04	5.92E-07	9.88E-06	3.32E-06
Lead (Pb)	-4.72E-04	-7.08E-05	8.38E-05	-5.09E-04	1.76E-05	5.92E-06
Mercury (Hg)	3.05E-06	-1.71E-05	1.56E-05	1.95E-07	3.26E-06	1.09E-06
Miscellaneous Chemicals						
Volatile Organic Compounds (VOCs)	1.69E+02	-2.61E-01	0.00E+00	-2.46E-02	9.40E+01	7.53E+01

[a]The functional unit is per ft^2 of barrack removed. The emissions in this table are expressed in terms of g/ft^2 of barrack removed.
[b]Equipment includes a lift, bobcat, excavator, chopsaw, chainsaw and weedeater.
[c]Transportation includes labor and equipment.

TABLE 5. Emissions from the scenario involving 44% manual methods[a]

Emission	Total	Salvaged Material	Disposal	Recycled Material	Equipment[b]	Transportation[c]
Criteria Pollutants						
Carbon Monoxide (CO)	2.22E+03	-8.04E+01	7.09E+01	9.36E-01	1.17E+03	1.06E+03
Nitrogen Oxides (NO_x)	4.69E+01	-6.84E+01	4.90E+01	-9.59E-01	3.83E+01	2.90E+01
Air Toxics						
Dioxin	-6.99E-12	-2.68E-11	1.53E-11	1.87E-13	3.46E-12	8.65E-13
Greenhouse Gases						
Methane (CH_4)	9.84E-01	-2.22E+00	2.48E+00	3.03E-02	5.57E-01	1.37E-01
Carbon Dioxide (CO_2)	5.29E+02	-1.42E+03	1.61E+03	-2.72E+02	5.22E+02	8.92E+01
Metals						
Arsenic (As)	6.68E-05	-1.46E-04	1.97E-04	5.92E-07	1.09E-05	2.67E-06
Lead (Pb)	-2.99E-03	-7.50E-05	9.49E-05	-3.04E-03	2.13E-05	5.28E-06
Mercury (Hg)	4.06E-06	-1.66E-05	1.60E-05	1.96E-07	3.58E-06	8.79E-07
Miscellaneous Chemicals						
Volatile Organic Compounds (VOCs)	1.04E+02	-2.53E-01	0.00E+00	-2.46E-02	5.38E+01	5.02E+01

[a]The functional unit is per ft^2 of barrack removed. The emissions in this table are expressed in terms of g/ft^2 of barrack removed.
[b]Equipment includes a lift, bobcat, excavator, chopsaw, chainsaw and weedeater.
[c]Transportation includes labor and equipment.

TABLE 6. Emissions from the scenario involving 26% manual methods[a]

Emission	Total	Salvaged Material	Disposal	Recycled Material	Equipment[b]	Transportation[c]
Criteria Pollutants						
Carbon Monoxide (CO)	1.62E+03	-6.76E+01	7.85E+01	9.36E-01	8.15E+02	7.94E+02
Nitrogen Oxides (NO_x)	4.96E+01	-5.75E+01	5.43E+01	-9.59E-01	3.20E+01	2.18E+01
Air Toxics						
Dioxin	-5.34E-13	-2.25E-11	1.70E-11	1.87E-13	4.13E-12	6.49E-13
Greenhouse Gases						
Methane (CH_4)	1.69E+00	-1.86E+00	2.75E+00	3.03E-02	6.67E-01	1.03E-01
Carbon Dioxide (CO_2)	9.69E+02	-1.19E+03	1.78E+03	-2.72E+02	5.75E+02	6.70E+01
Metals						
Arsenic (As)	1.25E-04	-2.96E-04	3.91E-04	1.18E-06	1.30E-05	1.96E-06
Lead (Pb)	-2.97E-03	-6.30E-05	1.05E-04	-3.04E-03	2.55E-05	3.96E-06
Mercury (Hg)	8.85E-06	-1.40E-05	1.77E-05	1.96E-07	4.29E-06	6.60E-07
Miscellaneous Chemicals						
Volatile Organic Compounds (VOCs)	7.38E+01	-2.13E-01	0.00E+00	-2.46E-02	3.64E+01	3.76E+01

[a]The functional unit is per ft^2 of barrack removed. The emissions in this table are expressed in terms of g/ft^2 of barrack removed.
[b]Equipment includes a lift, bobcat, excavator, chopsaw, chainsaw and weedeater.
[c]Transportation includes labor and equipment.

TABLE 7. Emissions from the scenario involving 100% mechanical methods[a, b]

Emission	Total	Salvaged Material	Disposal	Equipment[b]	Transportation[c]
Criteria Pollutants					
Carbon Monoxide (CO)	2.52E+02	-3.58E+00	1.18E+02	4.85E+01	8.92E+01
Nitrogen Oxides (NO_x)	8.77E+01	-3.05E+00	8.13E+01	6.40E+00	3.04E+00
Air Toxics					
Dioxin	2.62E-11	-1.19E-12	2.54E-11	1.70E-12	2.66E-13
Greenhouse Gases					
Methane (CH_4)	4.34E+00	-9.87E-02	4.12E+00	2.75E-01	4.28E-02
Carbon Dioxide (CO_2)	2.19E+03	-6.63E+00	1.99E+03	1.79E+02	2.78E+01
Metals					
Arsenic (As)	3.29E-04	-6.46E-06	3.28E-04	5.36E-06	8.34E-07
Lead (Pb)	1.50E-04	-3.06E-06	1.42E-04	9.51E-06	1.48E-06
Mercury (Hg)	2.77E-05	-7.40E-07	2.64E-05	1.77E-06	2.74E-07
Miscellaneous Chemicals					
Volatile Organic Compounds (VOCs)	6.18E+00	-1.13E-02	0.00E+00	2.01E+00	4.18E+00

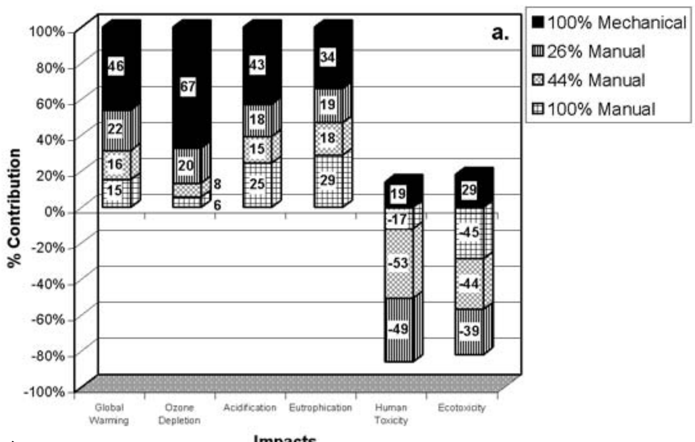
[a]The functional unit is per ft^2 of barrack removed. The emissions in this table are expressed in terms of g/ft^2 of barrack removed.
[b]Recycled Material is not applicable for 100% mechanical. Hazardous waste not accounted for in all 4 scenarios.
[c]Equipment includes a bobcat, excavator and weedeater.
[d]Transportation includes labor and equipment.

drove to the site decreased as fewer manual methods were used, which, in turn, decreased the NO_x production from the combustion of the gasoline. The 100% Mechanical scenario yielded the highest NO_x emissions because the steel was not recycled. The recycling of steel produced negative emissions of NO_x (emissions savings) for the manual deconstruction scenarios, thus allowing 100% manual deconstruction to yield lower NO_x emissions than 100% mechanical demolition.

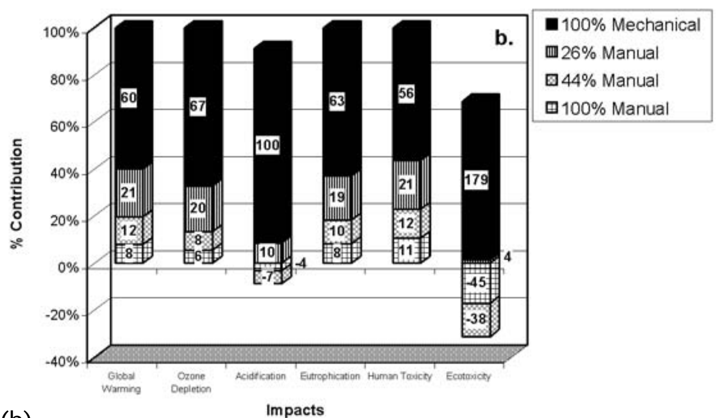
Impact Analysis

An impact assessment was performed on each of the four scenarios to determine their effects on Global Warming, Ozone Depletion, Acidification, Eutrophication, Human Toxicity, and Ecotoxicity. As stated earlier, two published impact assessment methods, EDIP and CML 2000, were used for this LCA to compare and contrast the results of two hypothetical cases—1) with salvage and reuse of the salvaged materials in the region of the deconstruction activity and 2) with salvage, transportation to the Habitat for Humanity warehouse in Austin, TX, and subsequent reuse of the salvaged materials.

Case 1: Salvaging and Nearby Reuse of Material. Figures 2a and 2b show the impacts calculated using the EDIP and CML 2000 impact analysis methods for each of the four scenarios where material is salvaged and delivered to local reuse and recycling facilities. These bar charts show the percent each scenario contributes to the total impact contribution from all four scenarios and provides a convenient relative measure of the impacts resulting from all scenarios



(a)



(b)

FIGURE 2. Impacts of all scenarios with local reuse of salvaged materials (Case 1). Impacts calculated using (a) EDIP method and (b) CML 2000 method. [The numbers on or next to each bar represent the individual scenario's percent relative contributions towards each impact. Negative percent contributions denote savings to the individual impact compared to the 100% Mechanical scenario.]

considered. For example, when considering Global Warming, the 100% Mechanical scenario contributed 46% towards the total summed Global Warming impacts of all four scenarios. The EDIP impact results (Figure 2a) show that the 100% Mechanical scenario yielded higher percent contributions to all impacts compared to the scenarios involving manual methods. The impacts to Human Toxicity and Ecotoxicity show negative percent contributions from the manual methods, a direct result of each scenario yielding savings in emissions (reflected in Tables 4–6) and resulting avoided impacts. Human Toxicity, Ecotoxicity, and Ozone Depletion impact values were most critically influenced by the 100% Mechanical scenario, with 73%, 72%, and 61% difference in percent contributions, respectively, between the 100% Mechanical scenario and the manual scenario with the lowest value in each category. When comparing the scenarios with the highest and lowest actual impact values, rather than the differences in percent contributions to each impact, the greatest differences were also observed in Human Toxicity (6.36E+13 from the 100% Mechanical and -8.31E+13 from the 44% Manual scenarios), Ecotoxicity (1.16E+06 from the 100% Mechanical and -1.83E+06 from the 100% Manual scenarios), and Ozone Depletion (0.0243 from the 100% Mechanical and 0.00202 from the 100% Manual scenarios).

Comparing only the manual methods, the 100% Manual scenario yielded the lowest impacts to Global Warming and Ozone Depletion, whereas Acidification and both toxicity impacts were lowest in the 44% Manual scenario. Eutrophication impacts were lowest in the 44% and 26% Manual scenarios, whereas Ecotoxicity impacts were the lowest in the 100% and 44% Manual scenarios, both yielding largest negative impact values. These small differences in impacts involving manual methods were directly related to the amount of wood salvaged and to the amounts of diesel fuel, gasoline and electricity used in the processes. Manual deconstruction avoided the production of virgin wood, thus avoiding electricity emissions from this stage and yielding decreases in the Ecotoxicity, Ozone Depletion and Global Warming impacts. The 100% Manual scenario, involving increased use of machinery and cars, yielded higher Human Toxicity, Acidification and Eutrophication impacts than its other manual counterparts.

Like the EDIP method results, the CML 2000 method yielded the highest impacts from the 100% Mechanical scenario in this case that considered salvaging with nearby reuse of materials option. The CML 2000 approach also showed that the 100% Manual scenario yielded the lowest impacts in all categories except Acidification, which was lowest in the 44% Manual scenario (Figure 2b). In comparing only the impacts from the manual scenarios, the 26% Manual scenario was largest in all cases and yielded no negative impacts using the CML 2000 method.

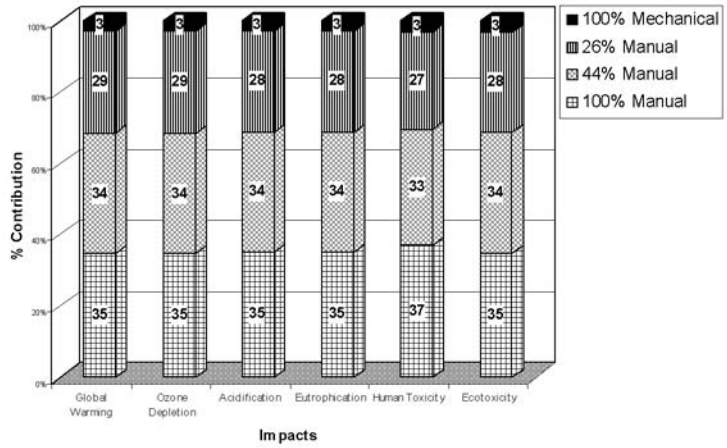
Case 2: Salvaging and Transport to Austin, TX for Reuse. The impacts determined by the EDIP method for each of the four scenarios that included transportation of the salvaged materials to the Habitat for Humanity warehouse in Austin, TX (approximately 885 miles) is shown in Figure 3. The trends resulting from the CML 2000 method of quantification of impacts were the same as resulting from the EDIP method and are thus not shown. The 100% Mechanical scenario yielded the lowest impacts in all instances because of its significantly lower transportation requirements.

The transportation of the salvaged material to Austin, Texas increased the environmental impacts for each of the scenarios in which materials were salvaged. Likewise, impacts increased with increasing manual involvement because of the greater emissions related to fuel production and use during transportation accompanying the larger weight of salvaged materials. Both the EDIP (Figure 3) and CML 2000 (not shown) impact results emphasize the negative influence of transportation of the salvaged materials to a storage facility out of the region of the deconstruction activity. In this case where the materials were transported approximately 885 miles, the negative impacts resulting from increased emissions involved in transportation far outweighed the savings in emissions that occur by reusing the materials.

Sensitivity Analysis

The previous results show the influence of both material salvaging for reuse and transportation to a storage warehouse on the environmental and health impacts of each scenario compared. Other variables

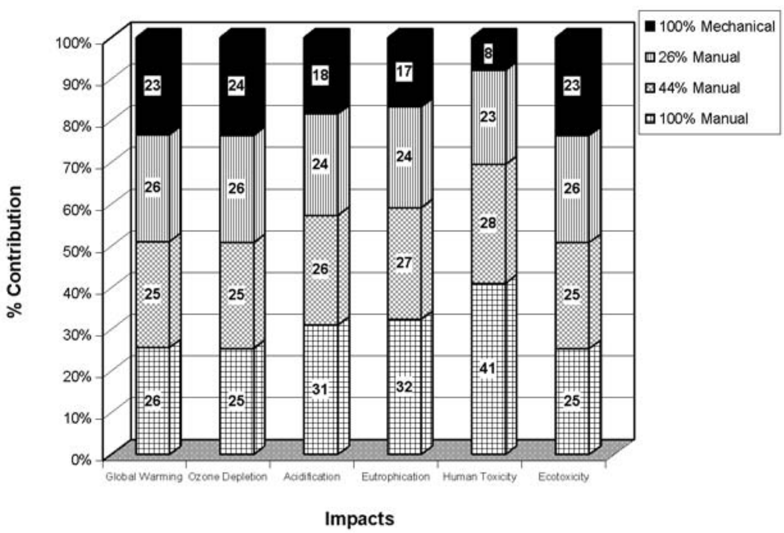
FIGURE 3. Impacts calculated by EDIP method of all scenarios with transport to the Habitat for Humanity warehouse in Austin, Texas (Case 2). [The numbers on or next to each bar represent the individual scenario's percent relative contributions towards each impact.]



tested for their influence on impacts were salvaging, commuting distance, transport distance of equipment and materials, degree of recycling, and time for material preparation.

No Salvaging After Deconstruction. To determine the positive effects of salvaging on the impacts of interest, no reuse of the salvaged material was considered, thus representing a situation where no reuse options are available. While it is unlikely that deconstruction would be pursued given no available reuse applications (except in urban areas where use of heavy equipment in building removal is precluded), this case provided a boundary condition for a broad comparison of results from the previous two cases discussed. In this option, all salvaged materials are disposed of in a landfill, and virgin wood production (shown in Figure 1) is not avoided in the manual scenarios. All scenarios that involve manual deconstruction show comparable or larger contributions to all impact categories calculated by the EDIP method (Figure 4), compared to the mechanical demolition scenario. All of the environmental impacts were lowest for the 100% Mechanical scenario because of the lower emissions resulting from lower total mileage for transportation of the employees to/from the site and the lowest total hours of equipment use. Specifically, Ecotoxicity and Human Toxicity impacts were

FIGURE 4. Impacts calculated using the EDIP method of all scenarios and not including reuse of salvaged materials. [The numbers on or next to each bar represent the percent relative contributions of each scenario towards each impact.]



higher in the scenarios involving manual methods because of the increased need for diesel fuel and gasoline for machine and automobile operation, respectively. These impacts are most affected by the emissions of mercury and lead during the production of the fuels, not emissions resulting from their use in the associated equipment. Global Warming contributions from the manual scenarios were 2-3% higher compared to the mechanical scenario, mostly because of the increased CO_2 and CO emissions from increased transportation (and thus fuel) requirements of the workers.

The increase in machine and transportation requirements in all of the manual scenarios also yielded increased SO_x and NO_x emissions that increased Acidification and Eutrophication impacts. Most of the SO_x emissions were released during the production of the diesel fuel and gasoline required by the machines and automobiles, whereas NO_x emissions were released primarily during the use of these fuels.

The Ozone Depletion potential was elevated because of the increased production requirements of diesel fuel, needed in larger quantities in the manual scenarios. The production of diesel fuel involves CFC emissions, thus yielding increased ozone depletion impacts. Regardless of the impact considered, however, these results show that, if the salvaged materials are not reused, manual methods of deconstruction yield potential for increased or comparable impacts compared to traditional demolition methods.

Commuting Distance and Carpooling. The round-trip commuting distance of 20 miles assumed in the baseline case was increased and decreased by 5 miles, and the number of people/car of 1 in the baseline case was increased to 4 to determine the sensitivity of these variables on the impacts from the 100% Manual scenario. The importance of carpooling to the site by increasing the number of occupants to four was evident by a decrease in eutrophication by 561%, in acidification by 77.5%, and in human toxicity by 39%. Less dramatic results were observed after increasing the driving distance by 5 miles, where the largest changes were observed in impacts on eutrophication, acidification and human toxicity (2.12%, 0.290% and 0.146% increases, respectively).

Distance of Materials and Machinery Transport. Driving distances for transportation of demolition equipment, salvaged material, recycled material and landfill material, for moving equipment to the woods, felled wood from the harvest site to the mill and boards from the mill to the store or site were increased and decreased by 5 and 10 miles from their assumed transport distances (listed in the Assumptions and Limitations section). Most of the emissions categories did not increase or decrease significantly as a result of these changes in transport distance. Those impacts influenced the greatest were Global Warming, Ozone Depletion, Acidification, and Eutrophication, a direct result of elevated emissions resulting from increased diesel fuel requirements. For example, when the mileage of an eighteen-wheel truck was increased by 5 miles, eutrophication increased by 18.3%, Acidification increased by 2.38%, Global warming increased by 2.11%, and Ozone Depletion increased by 1.25%.

Recycling. When recycling of materials was not considered in the scenarios involving manual methods, Acidification, Eutrophication, and Ecotoxicity were impacted to the highest degree in the 100% Manual scenario, with increases of 23.5%, 36.4% and 77.9%, respectively. Here, any recyclable material would be landfilled, resulting in increasing impacts caused by the virgin material requirements.

Time Required for Paint and Nail Removal. According to the deconstruction team's past experience, 30% of the total time for manual deconstruction involves handling, denailing, trimming, stacking and loading for transport or site storage. The use of the generator in this scenario was assumed to account for stripping and denailing of the wood. However, this time percentage was increased and decreased by 5 and 10% to account for differences in methods and experience levels of deconstruction teams. The results show that large changes in Acidification, Eutrophication and Human Toxicity occur when the generator times for paint stripping and denailing runs were altered. Acidification increased the most, 106%, when the time for material preparation was increased by 5%, while Eutrophication and Human Toxicity impacts increased by 48.5% and 26.1%, respectively. Thus, the amount of time spent on material preparation can greatly affect the environmental impacts that occur from manual deconstruction.

CONCLUSIONS

Of the three cases considered for handling salvaged materials, the one involving salvaging and reuse within a 20-mile distance yielded the lowest impacts. Both the CML 2000 and EDIP impact assessment methods resulted in significantly lower environmental and health impacts when manual methods of deconstruction were used. Of the three manual scenarios considered with salvaging, the 100% and 44% Manual scenarios yielded, for the most part, the lowest impacts. Compared to the scenarios involving manual methods of deconstruction, the 100% Mechanical scenario required the lowest time commitment, as anticipated, and, if the option of not using salvaged wood to replace virgin wood in any of the four scenarios is considered, this traditional means of building removal was shown to be the best option in terms of environmental emissions and resulting impacts. However, if the reuse of salvaged wood is assumed to avoid the production of virgin wood, then either the 100% Manual or 44% Manual scenario would be preferred because of the decrease in environmental emissions and thus impacts. The LCA model presented herein is most sensitive to changes in car mileage and the amount of time the generator runs. Therefore, all planning stages of deconstruction activities should take into account the location of materials reuse, the commuting distance of the workers, and the amount of time spent on material preparation.

Social and economic impacts of deconstruction and demolition processes were not quantified in this study. Economic impacts of deconstruction have been discussed by Guy and Williams (2004) and Guy (2006a), however. Because deconstruction is more time- and labor-intensive, it provides work for a crew for several days. Deconstruction also provides lower-cost building materials, thus lowering the cost of new construction and enabling those unable to afford virgin materials to buy materials of good quality for repairs on their own homes. Given that the Department of Defense must dispose of nearly 2.5 million square feet of army barracks in the U.S. EPA Region 4 alone, incorporating some degree of manual deconstruction offers potential benefits well beyond those quantified in this study. Given the influence of transportation of salvaged materials for reuse applications, it is most recommended, however, that a strategy be developed to foster reuse within the deconstruction site's region.

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