Carbon Footprint of Alternative Wood Product Retirement Strategies

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Abstract: Like many undergraduate and graduate engineering programs, the Master of Engineering (MEng) program in Sustainable Engineering at the Rochester Institute of Technology (RIT) concludes when students have completed a capstone project. As currently implemented capstone projects can be individual or group projects. Students engaged in capstone typically investigate specific problems for both on and off-campus clients. Projects are overseen by a faculty member and project deliverables typically include a formal project writeup as well as a summary presentation to the faculty supervisor and the clients. This article describes the findings of a two semester capstone project that was commissioned to investigate the environmental consequences that arise from several alternative wood product end of life retirement strategies. Results suggest that for wood products and other similar items (those fabricated from high carbon content, biodegradable materials) recycling and combustion strategies at end of life may ultimately generate more greenhouse gas emissions than a landfill strategy.

Introduction

The Sustainable Engineering graduate program at the Rochester Institute of Technology, is offered in two modes. Students enrolled in the Master of Science in Sustainable Engineering (MSSE) must complete a traditional, independent research thesis and defend it before their research committee in order to graduate. The expectation is that the research thesis makes a unique contribution to the Sustainable Engineering body of knowledge. The MSSE program is designed to appeal to students who desire a true research experience and wish to cultivate their research skills. Students enrolled in the Master of Engineering in Sustainable Engineering (MESE) must complete an applied "capstone project" in order to graduate. Students can engage capstone projects as part of a team, or they can work individually to fulfil the requirement. Usually, students working on a capstone project investigate and attempt to resolve a specific applied problem for a client. The MESE program is designed to serve students who are more applications oriented, or who aren't comfortable with the uncertainties of research.

The MESE capstone is meant to serve as a summary experience, and there is the expectation that students utilize concepts and tools that were acquired through the Sustainable Engineering curriculum. The projects are developed and overseen by a faculty capstone coordinator. The capstone coordinator cultivates and develops projects in concert with potential clients. Project clients can be internal, on campus individuals/organizations as well as external, off campus entities such as governmental organizations, charities, and private sector concerns.

This report describes the findings from an atypical capstone project. The work reported here emerges from a capstone project where the student partnered with a faculty client to explore an open ended research question, rather than engage in a more routine applied project with specified deliverables. This approach represents something of a halfway point between the research focused MSSE degree program and the traditional applications oriented MESE program.

This project was undertaken to study the environmental impact (specifically the greenhouse gas emissions) associated with the end of life disposition of wood products. The analysis offered here combines findings from the literature describing the carbon content of wood species and literature evaluating greenhouse gas emissions arising from aerobic and anaerobic decomposition of wood.

The paper is organized as follows:

The initial section will describe a general product life cycle model and overview the ways in which products are likely to move through their life cycle stages. The next section will describe the domain of wood products and why they are of particular interest here. An analysis section will follow describing the carbon footprint calculations for the emissions that arise from the ultimate wood disposition strategies considered here. A discussion/conclusions section will summarize the findings and a final notes section will offer impressions on this atypical capstone approach.

A general product life cycle model

Figure 1 depicts a general product life cycle model.

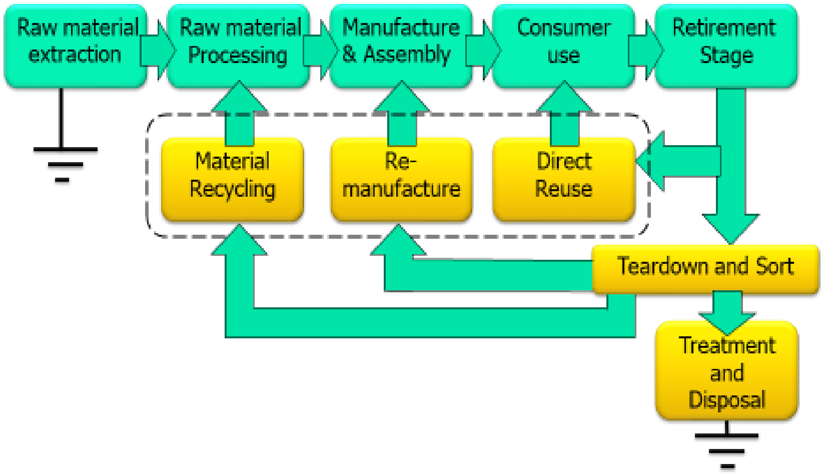

Figure 1. General Model of the Product Life Cycle

Raw Material Extraction: Most products are fabricated from a variety of materials, and those materials must be extracted from a fundamental source. Metals are refined from ores extracted from the earth. Plastics are created by refining petroleum and gas products extracted from underground. The raw materials for wood products are harvested from forests. These extraction operations can generate a variety of environmental impacts including local land transformation and degradation, water contamination, and greenhouse gas and other air emissions.

Raw Material Processing: Once the raw materials are available, they must be transported to processing centers where they can be transformed into the intermediate materials that are suitable for manufacturing purposes. Iron ore is transformed into steel products (sheets, beams, etc.), petroleum is refined into various plastics (polypropylene, vinyl, etc.), and logs are converted into a variety of intermediate wood materials (dimensional lumber, plywood, etc.). These raw material processing operations rely on energy and material inputs and generate their own environmental impacts.

Manufacture and Assembly: Intermediate materials must be transported to facilities where they will be combined with other materials to produce finished products. Again, manufacturing and assembly operations rely on a range of energy and material inputs, and they may generate environmental impacts of concern.

Consumer Use: Once a product has been generated, it moves through a supply chain and eventually ends up in the hands of a consumer. While in use by a consumer, a product may consume resources and/or generate environmental impacts of its own (i.e. a lawn mower consumes gasoline and generates greenhouse gas emissions). Eventually, the consumer will likely retire the product. The product might be retired for a range of reasons, including:

- the product is no longer needed
- the product is obsolete
- the product is no longer functional

Retirement: Depending on the design of the product, the context within which the product was designed, developed and sold, and the reason for the product's retirement, several options may be available for dealing with the product when the consumer chooses to dispose of it. These include:

- direct reuse: a product is transferred, essentially as is, to another consumer (as would happen with a used automobile that is "traded in" to purchase a new vehicle)
- remanufacture: a product is transferred to a facility where it may be taken apart, inspected, refurbished, and returned to service (as happens with many automotive components like alternators, and constant velocity joints)
- material recycling: the form of the product is destroyed and the materials are recovered (as occurs with waste cardboard boxes or aluminum beverage containers)
- treatment and ultimate disposal: if none of the previous disposition options are available, appropriate treatment and disposal procedures should be used for ultimate disposition. These methods can include remediation and release of gaseous or liquid wastes, biodegradation, and incineration and/or landfill of solid waste.

The Reuse, Remanufacture, and Recycling end of life strategies may prolong a product's useful life or extend the useful life of the materials from which a product is constructed. However, virtually all products will eventually be relegated to ultimate disposal. Likewise, material recycling methods tend to degrade materials at each iteration (a process known as "downcycling"). Eventually, recycled materials will no longer have required properties and will require ultimate disposition.

Characteristics of Wood Products

Wood products are ubiquitous. Wood is used to fabricate durable items (timber framing, dimensional lumber, furniture, flooring, etc.) as well as products with very short useful lives (paper goods, pencils, paint stirrers, one way pallets, etc.). Wood has many features that make it a useful raw material. Wood is widely available and relatively inexpensive. It exhibits good compressive and tensile characteristics. Wood is attractive and, in appropriate applications, it is highly durable. Wood also offers characteristics that are advantageous from a sustainability perspective. It is a natural product, and, when harvested appropriately, it is a renewable resource. It can be shaped and transformed using processes that are environmentally benign (cutting, turning, nailing, screwing, etc.), and in use it generates few if any harmful emissions.

Wood products follow essentially the same general product lifecycle described in Figure 1. Raw materials are harvested from the earth, the raw materials are processed into intermediate materials suitable for manufacture, those intermediate materials are transformed into products, those products are used by consumers, and eventually the products are retired. Environmental impacts including the generation of greenhouse gases may arise during all wood product life cycle stages. Importantly, even though the reuse, remanufacture, and recycle options may be available at the time of retirement, eventually wood products will require ultimate disposition.

Ultimate disposition of wood products may take several forms:

- the product may be left to biodegrade aerobically either in its original form or following transformation (landscaping mulch, animal bedding, etc.)
- the product may be incinerated, with or without energy recovery
- the product may be deposited into a landfill where it will degrade aerobically and anaerobically

This project focuses on the greenhouse gas emissions that arise during the ultimate disposition of wooden materials. The intent is to quantify the CO_2 equivalent emissions (CO_2 eq) that arise from the ultimate disposal of a fixed amount of wood. Specifically, we determine the CO_2 eq emissions associated with the ultimate disposal of 10 kilograms of wood via each of four ultimate disposition strategies:

- complete aerobic biodegradation
- incineration without energy recovery
- mixed aerobic and anaerobic biodegradation as would occur in a modern landfill
- incineration with energy recovery

Analysis

Carbon content of wood: Greenhouse gas emissions arising during the ultimate disposal of wood material obviously depend on the carbon content of the wood itself. The carbon content of wood varies from biome to biome, across species, and within species. Kim and Song [1] utilize the assumption that most woods contain about 50% carbon. Thomas and Martin [2] surveyed 31 published studies that reported 253 species-specific carbon content entries. Findings from these studies include:

- the maximum observed carbon content was 60.7%
- the minimum observed carbon content was 41.9%
- across biomes the mean carbon content for conifers (softwoods) was 50.8%
- across biomes the mean carbon content for angiosperms (hardwoods) was 47.7%

Here, in order to describe emissions from softwoods and hardwoods we consider the ultimate retirement CO_2 eq emissions from wood assuming carbon contents of 45%, 50%, and 55%.

CO_2 eq emissions under complete aerobic decomposition and incineration without energy recovery: Complete aerobic decomposition of wood and complete incineration of wood (without energy recovery) will result in the same greenhouse gas emissions. Under these two retirement strategies each of the carbon atoms in the retired wood will be pair with two oxygen atoms and be transformed into CO_2. Carbon has an atomic weight of 12, while a molecule of CO_2 has an atomic weight of 44. Therefore, each unit of carbon present in the wood will be converted to 44/12 = 3.67 units of CO_2 . CO_2 emissions corresponding to the disposal of 10 kg of wood for the 3 carbon concentration cases are shown in Table 1.

Table 1. CO_2 emissions from 10 kg of wood under aerobic decomposition or incineration without energy recovery

	Carbon Content of Wood		
	45%	50%	55%
CO_2 eq (kg)	16.50	18.33	20.17

To illustrate the calculations, consider the 55% carbon content case. Under this condition, 10 kg of wood will contain 5.5 kg of carbon. If all of the carbon in the wood is returned to the atmosphere by aerobic decomposition or incineration, 5.5 x 3.67 = 20.17 kg of CO_2 emissions will be generated.

CO_2 eq emissions under aerobic and anaerobic decomposition (landfill scenario): and incineration without energy recovery: When organic material such as wood is deposited in a modern landfill, it may undergo both aerobic and anaerobic decomposition. Both modes of decomposition generate greenhouse gases. As noted earlier, aerobic decay produces CO_2 . However, anaerobic decomposition results in the production of methane (CH_4), a greenhouse gas 21 times more potent than carbon dioxide [3].

There has been limited work on the degradation of wood in landfills [4][5][6]. For the work conducted here, two characteristics of wood degradation in landfills are of major interest: the fraction of the carbon in wood that decomposes under landfill conditions, and the relative amounts of CO_2 and CH_4 that are generated as wood decays anaerobically.

Micales and Skog [7] report that 0% – 3% of the carbon from wood is released into the atmosphere as CO_2 and CH_4 once the material has been landfilled. Wang et al [4] observed the decomposition of 4 wood species in laboratory scale landfills, and reported carbon conversion rates of 0.0%, .1%, 1.8%, and 7.8% for eucalyptus, radiata pine, spruce, and red oak, respectively. For this study we will examine cases with carbon conversion rates of 1%, 3%, 5%, and 7%. Micales and Skog [7] suggest that landfill gas is emitted as 60% CH_4 and 40% CO_2. However, Wang et al [4] assume that landfill decomposition generates one mole of CO_2 for every mole of CH_4. The calculations here invoke this same assumption.

Based on the assumptions outlined above, the greenhouse gas emissions for landfilled wood can be calculated for several decomposition cases. Table 2 summarizes the greenhouse gas emissions from landfilled wood with varying carbon content at several decomposition fractions.

Table 2. CO_2 eq emissions from 10 kg of wood, landfill decomposition

	Carbon decomposition			
	1%	3%	5%	7%
45% carbon content (kg CO_2 eq)	0.712	2.137	3.562	4.987
50% carbon content (kg CO_2 eq)	0.792	2.375	3.958	5.542
55% carbon content (kg CO_2 eq)	0.871	2.612	4.354	6.096

To illustrate the calculations, consider the case of wood with 55% carbon content in a landfill where 5% of the carbon content of the wood will degrade. 10 kg of such wood will contain 5.5 kg of carbon. Of that carbon, only 5%, or .275 kg, will degrade under landfill conditions. Half of the .275 kg of carbon (.1375 kg) will transform into .5042 kg of CO_2. The remaining carbon will become .1833 kg of CH_4. The greenhouse gas potential of .5042 kg of CO_2 is .504 kg CO_2 eq. The greenhouse gas potential of .1833 kg of CH_4 is .183 x 21, or 3.850 kg CO_2 eq. Total greenhouse gas emissions for this scenario are 4.354 kg CO_2 eq.

Note that the greenhouse gas emissions from landfilled wood are much lower than those from aerobic decomposition or incineration, even when a very high (7%) landfill decomposition fraction is assumed. For instance, for wood with 55% carbon content, the emissions arising under the worst greenhouse gas scenario considered in Table 2 (7% decomposition fraction) are 30% of those arising from aerobic decomposition or incineration as shown in Table 1 (6.096 kg CO_2 eq vs 20.17 kg CO_2 eq). Even though the aerobic decomposition that occurs in landfills generates CH_4, a much more potent greenhouse gas than CO_2, the fraction of carbon that is converted into CH_4 and CO_2 in the landfill is so small that the overall greenhouse gas potential from landfill emissions is reduced dramatically from that observed under aerobic decomposition or incineration.

CO_2 eq emissions under incineration with energy recovery: Incineration of wood products at the time of ultimate disposal emits greenhouse gases but also generates useful heat energy. If the wood is landfilled, very little, if any heat energy will be recovered (for our purposes, we are ignoring the small amount of heat energy that might be harvested from a landfill that is designed to capture, clean and combust anaerobically produced methane). Clearly, the strategy to landfill wood at ultimate retirement generates fewer greenhouse gas emissions than incineration. However, to fairly compare the emissions from a landfill disposal scenario to those from an incineration strategy, we must expand the landfill scenario to include heat generation capability equivalent to that of the wood incineration system.

When combusted, 10 kg of wood with 50% carbon content will produce 18.33 kg of CO_2 eq emissions (Table 1) and recoverable heat energy. Table 3 provides low and high heating values for the combustion of hardwoods and softwoods [8]. Our calculations will use the average of the two values.

Table 3. Heating values for hardwoods and softwoods

	Low heat value (MJ/kg)	High heat value (MJ/kg)	Average heat value (MJ/kg)	Heat from 10 kg wood (MJ)
Hardwood heat content	19.80	21.30	20.55	205.5
Softwood heat content	20.70	22.10	21.40	214.0

The last column in Table 3 describes the heat energy that is generated when 10 kg of hardwood or softwood is incinerated.

The heat recovered from incineration of wood is likely used to replace or offset heat that would be provided by fossil fuels in furnaces, boilers, kilns, etc. A fair comparison of the incineration and heat recovery retirement practice to landfilling requires that we expand the landfilling strategy to include generation of heat from fossil fuels.

Table 4 lists emissions associated with combustion of commonly used fossil fuels [9]. In addition, the table provides the greenhouse gas emissions that would result from combustion of amount of each listed fuel that would provide the energy equivalent to the incineration of 10 kg of softwood (214.0 MJ) and 10 kg of hardwood (205.5 MJ). These emissions should be added to those associated with landfilling in order to fairly compare the overall emissions from incineration (with heat recovery) and landfilling (with heat generation).

Table 5 summarizes the emissions generated when softwood is landfilled (50% carbon content is assumed) and heat energy is created by combustion of various fossil fuels. Table 6 provides the same information for landfilled hardwood.

Table 4. CO2 Emissions values from fossil fuel combustion

	CO_2 emissions (kg CO_2/MJ)	Emissions equivalent to 10 kg softwood combustion (kg CO_2 eq)	Emissions equivalent to 10 kg hardwood combustion (kg CO_2 eq)
anthracite	0.0983	21.036	20.201
diesel	0.0693	14.830	14.241
gasoline (non-ethanol	0.0676	14.466	13.892
propane	0.0589	12.605	12.104
natural gas	0.0503	10.764	10.337

Table 5. CO_2 eq emissions from landfill of 10 kg softwood plus equivalent heat generation from fossil fuels (bold entries represent CO_2 eq emissions below those observed with the incineration disposition strategy.

	Carbon decomposition fraction			
	1%	3%	5%	7%
	Values are kg CO_2 eq			
anthracite	21.828	23.411	24.994	26.578
diesel	**15.622**	**17.205**	18.788	20.372
gasoline (non ethanol)	**15.258**	**16.841**	18.424	20.008
propane	**13.397**	**14.980**	**16.563**	**18.147**
natural gas	**11.556**	**13.139**	**14.722**	**16.306**

Table 6. CO_2 eq emissions from landfill of 10 kg hardwood plus equivalent heat generation from fossil fuels (bold entries represent CO_2 eq emissions below those observed with the incineration disposition strategy)

	Carbon decomposition fraction			
	1%	3%	5%	7%
	Values are kg CO_2 eq			
anthracite	20.993	22.576	24.159	25.743
diesel	**15.033**	**16.616**	**18.199**	19.783
gasoline (non ethanol)	**14.684**	**16.267**	**17.850**	19.434
propane	**12.896**	**14.479**	**16.062**	**17.646**
natural gas	**11.129**	**12.712**	**14.295**	**15.879**

Conclusions/Discussion

Recall (Table 1) that direct incineration of 10 kg of wood with 50% carbon content will generate 18.33 kg CO_2 eq emissions. Also, recall that combustion of 10 kg of wood will generate recoverable heat energy, about 205.5 MJ for hardwood combustion and 214 MJ for softwoods. Tables 5 and 6 describe the emissions that would be observed if the ultimate disposition strategy were to landfill the 10 kg of wood and replace the heat generated from wood combustion with heat generated from fossil fuel combustion. The bold entries in Tables 5 and 6 occur where the landfill/fossil fuel disposition approach generates fewer greenhouse gas emissions than the direct incineration/heat recovery option.

That the overwhelming number of cases considered (26 out of 40) favor landfilling and fossil fuel heat generation over the direct incineration approach is striking. Cases where the incineration option is favored are those where the fraction of landfill carbon degraded is high, the replacement fossil fuel generates a large amount of greenhouse gas, or a combination of these two scenarios. Where landfill carbon degradation occurs at low levels and “clean” fossil fuels are available, the landfill/fossil fuel approach exhibits lower total emissions. 18 of the 40 landfill/fossil fuel cases examined offer emissions more than 10% below emissions from the incineration case. 8 of the 40 cases report landfill/fossil fuel emissions more than 20% below the emissions reported for the incineration approach.

These results suggest that combustion of wood waste for energy recovery may not be an environmentally responsible disposal strategy when properly designed landfills or low carbon fossil fuels are available. It may be more appropriate, from a greenhouse gas perspective, to retire wood materials to landfill rather than to combust them. Available research suggests that very little (less than 10%) of the carbon in wood is transformed into greenhouse gases under landfill conditions. Perhaps the disposition of wood material in landfills represents a potentially useful carbon sequestration approach. After all, during their growth phase trees extract carbon directly from the atmosphere. Depositing wood material underground at end of life where it may be sequestered indefinitely could be helpful in reducing the level of atmospheric greenhouse gases.

We must emphasize that this preliminary analysis is manifestly incomplete. Simplifying assumptions have been invoked and important concerns have been omitted. For instance, modern landfill designs include technologies to accelerate decomposition and harvest the methane generated from anaerobic decay. The ability to capture methane generated from landfill might help tip the scales of this analysis even further in favor of the landfill/fossil fuel retirement approach. On the other hand, this analysis has omitted the carbon overhead required to make fossil fuels available for combustion. It takes energy to extract, refine, and transport fossil fuels. The analysis here has considered only the heating value of the end product fossil fuels. It has not considered the greenhouse gas implications of making those fuels available. Future work will take up some of these assumptions and omissions.

Final pedagogical notes

Much of the work for this project was carried out as an atypical, open ended capstone project in fulfillment of the requirements for the Master of Engineering in Sustainable Engineering. At the conclusion of the research, the capstone student drafted a summary paper [10] and evaluated the project from a pedagogical point of view. The results are of course anecdotal, but of interest nonetheless. The student who conducted much of the research cited 3 aspects of this project that resonated most deeply with him.

The nature of the research problem: The capstone project was offered to the student as an independent applied research problem: "What happens to solid wood at the end of its useful life, and what are the greenhouse gas implications?" Research on open ended problems can be uncertain, time consuming, even frustrating. However, the student accepted these challenges and believed that real advantages accrued from working on this type of project.

- "These types of open ended projects allow the student to form their own ideas and approach towards a solution rather than following a previously outlined sequence of steps"
- "These benefits include students being able to identify their inspiration or passion by having more freedom compared to alternative projects."
- "This open ended project inspired the student to take a detailed look at many different products and left the student with an enlightened outlook on how the products human use every day can impact the environment. Even though the project was "finished" in terms of the semester, the student gained a holistic understanding of a new educational topic."

The opportunity for the student to become the teacher: In the course of performing the research work for this project the student faced numerous occasions where he had to explain topics, methods and results to the capstone advisor. This seems to have promoted a deeper understanding of the material than might have occurred in a more traditional project.

- The approach to this project allowed "the student to become the expert and educate others".
- "In the case of this project, the student had no prior knowledge on wood varieties or the retirement scenarios associated and allowed the student to adapt and investigate the different topics that interested the student."
- "… this freedom allows for independent growth of their own knowledge on a subject at their own pace and then consult their professor."
- "This approach has proven to allow for an open free-thinking mindset that could ultimately generate conclusions that differ from the middle of the road common thinking."
- "There is value in allowing the student to think and learn for themselves."

The freedom to not worry about grading: This capstone project was set up as a contract. Once final deliverables had been completed satisfactorily, an agreed upon grade would be issued. This student seemed to respond very favorably and very much appreciate this minor alteration to traditional grading practices:

- "… when certain sources of stress are removed from the classroom the student is allowed to fearlessly excel and think differently from what the professor intended."
- "Rather than the student's mind being consumed with due dates or fear of not getting that "A+" the student can spend that brain power on a new innovative approach to a problem."

The student closed his observations with a final note on the value of open ended inquiry:

- "Rather than telling a student what or how to think, it is the educator's duty to provide the students with the tools to do the thinking and learning on their own. This is where the true value in engineering education ultimately lies."

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