IDENTIFYING BARRIERS TO WASTE DIVERSION: IMPROVING COLLECTION AND QUALITY OF CONSTRUCTION AND DEMOLITION WASTE FLOW INFORMATION

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Abstract

The majority of US construction and demolition (C&D) wastes flows are currently landfilled, which represents a significant source of underutilized resources and environmental degradation. Growing public concerns have increased the demand for C&D waste product recovery firms to reduce the landfilling of C&D wastes. Despite C&D wastes being one of the US's largest solid waste flows, there is a lack of collection and reporting on US construction sector wastes. This is disconcerting to waste product recovery firms who would benefit from C&D waste flow information to support their exploration of wants and uses of potential C&D wastes, development of competitive business strategies and operational planning.

This thesis contended that the lack of information on the US construction sector's C&D waste flows is a significant barrier to the optimal development of the C&D waste product recovery market. This thesis sought to address concerns over the collection and quality of information inherent in currently available C&D waste estimates for the US construction sector. The second chapter addressed the high levels of uncertainty and significant methodological shortfalls in existing national C&D waste estimates. A novel framework was developed to improve collection methods and the resolution of the data collected on C&D waste flows and composition. The framework included; measurement of data at the construction site, use of standardized reporting procedures, differentiation of renovation construction and renovation demolition wastes, accounting of construction materials stocked in buildings, characterization of materials at a product level and implementation of regulatory mechanisms. In the third chapter, a national stocks and C&D waste flows model was developed to determine structural wood product use, including softwood lumber, softwood plywood, OSB, glulam, I-joists and LVL, in US single family residences between 1950 and 2008. The results from this model demonstrated a product level of resolution in stocks and C&D waste flow estimates which revealed the variability of waste composition over time. The methodology used to develop the stock and flows

model may also be applied to estimate other C&D waste products, provided sufficient data were available.

Preface

I hereby declare that this thesis, as approved by my thesis committee and the Graduate Studies office, is the product of my original work and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

The core theme of this thesis is to address concerns over the collection and quality of information inherent in currently available C&D waste estimates for the US construction sector. I, Robert A. Sianchuk, was the main author in the conception and design, acquisition, analysis and interpretation of data, writing and revision of all chapters contained in this thesis up to the approval of the final draft. My supervisor, Dr. Paul McFarlane, provided substantial contribution to the conception and design, interpretation, writing and revision of all chapters contained in this thesis up to the approval of the final draft. The thesis, and the research to which it refers, contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution.

Revised versions of chapters two and three of this thesis will be submitted for publication.

Table of Contents

List of Tables

List of Figures

List of Equations

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Dedication

I dedicate this thesis to my mother Diana,

who is my foundation and inspiration.

My father Laurence,

who is the source of my shamelessness and extroversion.

And my uncle Peter and aunty Eileen,

who have been such a tremendous source of my personal development and positive experience in the wild wild west.

1 Introductory Chapter

1.1 US Construction Sector

The construction industry is the second largest economic sector in the United States (US), representing approximately 8% of annual GDP, and it is one of the largest consumers of raw materials and producers of waste products in North America (RocSearch Ltd 2005). However, there is very little information available on the material stocks and flows resulting from this sector's construction, renovation and demolition activities (Horvath 2004). This is a major concern as the majority of the waste flows, which are collectively known as construction and demolition (C&D) waste, are landfilled, representing a significant and unspecified flow of underutilized resources that are contributing to an overburdened environment (Brunner and Rechberger 2002, Cochrane et al. 2007, US EPA 2009b). Concerns regarding this issue are apparent from the current market demand for the services of waste product recovery firms involved in handling and processing C&D wastes diverted from landfills (US EPA 2009a). However, there are barriers to meeting this demand, as the current high landfilling rates also indicate that the growing C&D waste product recovery market has yet to effectively manage the US construction sector's C&D waste emissions. This thesis begins by exploring the role of C&D waste flows information as a barrier to the optimal development of C&D waste product recovery markets.

Economically and competitively positioning C&D waste product recovery operations is dependent upon the C&D waste flow opportunities that are pursued. Four main factors have been identified that reuse and recycling opportunities depend upon (Tchobanoglous et al. 1993):

1. Markets for the individual materials
2. Ability to process commingled C&D debris or to separate the individual materials
3. Economics of materials recovery
4. Materials specifications

In order to rationally assess each of these factors, it is apparent that information on the materials to be considered in reuse and recycling opportunities is a fundamental requirement. In this thesis the materials are C&D wastes. This thesis suggests that a complete set of information on C&D waste flows would include details the quality, quantity, location and time of emissions.

The need for improved C&D waste flow information was also identified in a survey of C&D waste industry stakeholders in California by the California Integrated Waste Management Board (CIWMB) where barriers to reuse and recycling were identified. The unpredictability and unreliability of C&D waste flows were found to be reasons why demolition is considered less costly than deconstruction and why there is a lack of recyclers and processors of C&D waste flows in California (CIWMB 2004). These consequences of unpredictable and unreliable C&D waste flows could be addressed with a complete set of information on C&D waste flows as this data could be used to forecast their availability. This would also enable firms to reduce deconstruction costs through strategic planning and explore potential market opportunities to economically and competitively divert C&D wastes.

This thesis contends that the collection and quality of information on the US construction sector's C&D waste flows are significant barriers to the optimal development of the C&D waste product recovery market. That is, this thesis suggests that a major factor for a waste product recovery market's to effectively and economically divert wastes, it would be beneficial to apply C&D waste flow information to explore diversion opportunities, guide decision making and develop competitive strategies. The quality of currently available C&D waste flow information is does not lend itself well supporting these areas due to significant uncertainties and shortcomings in the quality of data collection methods and reported estimates.

1.2 Thesis Themes and Objectives

The purpose of this manuscript style thesis is to address the collection and quality of information inherent in currently available C&D waste estimates for the US construction sector. This thesis also seeks to raise awareness that the optimal development of C&D waste product recovery markets are handicapped by the lack information on C&D waste flows. To achieve these purposes, two manuscript chapters on collection and quality of information on C&D waste flows being emitted from the US construction sector are presented.

The first manuscript chapter in this thesis, entitled *Developing the Reuse and Recycling Market: Improving Empirical Data Collection Methods to Increase the Applicability of US C&D Waste Estimates*, addresses the need for improving data collection. The purpose of this paper is to highlight the shortfalls and uncertainties contained in current national C&D waste flow estimates and propose a framework of methods to improve data collection and resolution.

The second manuscript chapter, entitled *Determining Stocks and Flows of Structural Wood Products in Single Family Homes in the United States*, provides C&D wood waste estimates at the product level, which is a higher resolution than currently available estimates at the national level for the US. The purpose of this paper is to develop a national stocks and flows model for structural wood product use in single family residences in the US between 1950 and 2009 and thereby provide important data on a key sector of the construction industry's activities. The approach used in this paper could be readily adapted to estimate stocks and flows of other important construction materials.

As indicated, these manuscript chapters are independent, and thus contain respective literature reviews. In this introductory chapter, the premise of this thesis is rationalized and the current literature on US construction sector C&D waste flow and composition is presented in order to contextualize the need for this thesis.

The following literature review outlines the importance of exploration as a key mechanism in reducing the assessment of C&D products as wastes. The need for improved information in order for a firm to explore its strategic value-adding applications is then reviewed. In the final section of this introductory chapter, information from current publications on US construction sector C&D waste flows are presented.

1.3 Literature Review

1.3.1 Waste and the Importance of Exploration

In this thesis, C&D wastes are defined as materials that are produced from the construction, renovation and demolition of buildings. They are not requirements, but consequent by-products of these construction activities and are subsequently not used or wanted. The following section discusses the subjectivity and role of exploration in the creation waste.

Solid waste is an unwanted or unusable material (Cheyne and Purdue 1995). However, as the concepts of unwanted or unusable imply that all wants and uses have been explored, evaluating materials as waste is subjective. In this context, exploration is the act of searching for information with the purpose of discovering wants and uses. Thus, it follows that, exploration is a key element to effectively reducing materials being evaluated as waste by discovering information that indentifies wants and uses for them.

The outcome of a failed exploration (ie. evaluation as waste) does not result in the same outcome for all material types. This is particularly evident when comparing the outcomes of raw resources and product materials with respect to their evaluation by the market, where buyers and seller exchange goods and services. That is, the result of a failed exploration for a waste raw resource is that it does not enter the market, as it is unwanted and unusable by buyers. In contrast, as products are goods that are already being bought and sold in the market, a failed exploration of wants and uses requires that it exit the market, thus creating what will be known in this thesis as a waste product flow.

Currently, the majority of waste product flows are disposed of in landfills (Cochrane et al. 2007, US EPA 2009a). The disposal of waste products represents a significant flow of underutilized resources which are contributing to an overburdened environment (Brunner and Rechberger 2002, US EPA 2009b). Furthermore, as landfilled waste products are not cycled or returned into the market, the creation of waste products is a root symptom of a linear economic system, which, under finite raw resource conditions, is by definition unsustainable (Hawken 1993). Thus, a primary objective of economies and business sectors pursuing sustainable solutions should be the collection and reporting of appropriate information on potential waste product flows in order to encourage the free exploration of their wants and uses and reduce the probability that they will create a waste product flow and be disposed of.

Segments of the US economy are pursuing sustainable solutions. This pursuit is in part being carried out by the US Environmental Protection Agency (EPA), which has recently released an assessment of business models that reduce energy, material, and water throughput while providing necessary goods and services. The goal of these models is to inform policies that align economic success and environmental stewardship (US EPA 2009b). Strong waste flow information intelligence is a key to the success of a number of US EPA models as they seek to optimize policy solutions spanning complete product life cycles (ie. cradle-to-grave).

This thesis focuses on addressing the available information on the US construction sector's C&D waste flows as it contends that the current lack of information in this regard is a significant barrier to the optimal development of a complementary C&D waste product recovery market. As the reason for collecting information on waste products has been established in this section, the following section places the role of information in a business context and discusses some of the challenges faced in collecting the C&D waste information needed by C&D waste product recovery firms.

1.3.2 Importance of Information

Research conducted on US construction sector C&D waste flows has reported that economics is the major barrier to diverting C&D wastes from landfills. These economic barriers include the high cost of collecting, sorting and processing low value recyclable materials in relation to the cost of virgin materials, and the low cost of landfilling C&D wastes (Franklin Associates 1998, US EPA 2009a). Further barriers include buildings and building products not being designed for recovery, locations not having recovery facilities, a lack of markets being defined and regulatory support (US EPA 2009a). However, this thesis contends that the majority of these economic barriers exist due to the absence of information, as it has restricted the ability of the C&D waste product recovery market to utilize these available resources by identifying combinations of products and services and create competitive value propositions. This contention directly supports the US EPA's strategy to overcome existing C&D waste recovery barriers by "expand[ing] recognition of the value of C&D materials so that they are more widely viewed as locally available resources rather than un-usable discards" (US EPA 2009a). This section expands upon this thesis's contention by highlighting applications of C&D waste flow information as a key to exploring wants and uses of C&D wastes and developing competitive business strategies.

Information is the key to guiding rational decision making in all firms, and the concept of superior information creating a competitive advantage in an imperfectly competitive market is well established in literature (Barney 1986, Alchian 1950, Mancke 1974, Rumelt 1984, Dierickx and Cool 1989). In considering the basic reverse logistics operations of the C&D waste product recovery market (below), C&D waste flow information is important to consider in planning operations, which begin with distribution (Pohlen and Farris 1992, Fleischmann et al. 1997).

Reverse Logistics Operations of C&D Waste Product Recovery Market:

- distribution planning; physical collection, testing, sorting, transportation and processing of C&D wastes from building construction, renovation and demolition sites.
- inventory management; balancing inputs to and outputs from inventory to ensure predictable service levels while minimizing holding costs.
- production planning; selection and transformation of C&D wastes inventories into the most economically attractive products.

Furthermore, C&D waste flow information can also be applied in key strategic value-adding applications such as enhancing market access, differentiating products and improving cost-effectiveness. For example, C&D waste flow information could be used to source strategic C&D waste flows in order to produce competitive products that derive market value at the lowest possible cost (Mowery and Rosenburg 1979). Further cost savings may be derived through supply chain information sharing, which can significantly reduce lead times and costs by enabling more efficient inventory management (Cachon and Fisher 2000). An inherent issue in the development of strategic value-adding applications and the aforementioned planning of operations are that they depend upon the quality of information available to them (Ives and Learmonth 1984, Fleischmann et al. 1997). Thus, poor information will result in ineffective or a lack of strategic value-adding applications and poorly coordinated operations.

Access to C&D waste flow information is instrumental in creating a rationally guided and competitive C&D waste product recovery market as firms require this information to plan operations and develop value-adding strategies with it. However, the market's success in this regard is dependent upon the characteristics of available C&D waste flow information. Thus, in order to support the optimal development of a highly competitive and rationally guided

C&D waste product recovery market, it is necessary to provide them with the highest quality C&D waste flow information.

The following section summarizes the current state of knowledge on C&D wastes emitted from the US construction sector and highlights the need to improve the collection and quality of information on C&D waste flows and composition. These topics are the focus of the two subsequent manuscript chapters of this thesis.

1.3.3 C&D Waste Flow Estimates for the US Construction Sector

This section introduces currently available information on national C&D waste flows and diversion rates for the US construction sector.

As stated earlier, there is very little information available on the material stocks and flows for the US construction sector. This is mainly due to the challenges inherent in collecting high quality empirical data on C&D wastes. These challenges primarily arise from the broad variations in quantity, quality and location of waste product emissions across sources, geographically and over time (as demonstrated in the third chapter). Although difficult to measure, the challenges involved in capturing the variations of C&D waste flows should be overcome in order to provide the most accurate and reliable information to C&D waste product recovery markets. Appropriately considering these variations is a key to designing and strategizing effective C&D waste data collections efforts (as detailed in the second chapter) that achieves the quality of information necessary to support the optimal development of the C&D waste product recovery market.

At a national level, these challenges make it quite costly to maintain ongoing empirical data collection surveys (Franklin Associates 1998, US EPA 2009a). This is one of the main contributing factors to the absence of an ongoing national survey that collects data on C&D product waste flows emitted from the construction, renovation and demolition of buildings in the US. Consequently, the few reports that have generated estimates of national C&D waste flows have compensated by developing unique estimation methods to extrapolate national data from very limited empirical data samples. With respect to the US construction sector, the US EPA has produced the only two national estimates that include all C&D waste material types, whereas researchers at the US Forest Products Laboratory (FPL) have produced the only four known single material type national estimates (Table 1.1).

Table 1.1 List of publications estimating national C&D waste emitted from the US construction sector.

Year(s) Estimated	C&D Waste Materials Included in Estimate	Publication
1990 to 1998	Wood Waste	McKeever 1999
1993	Wood Waste	Ince and McKeever 1995
1996	All	Franklin Associates 1998
1998	Wood Waste	Sandler 2003
2002	Wood Waste	McKeever 2004
2003	All	US EPA 2009a

The details of the US EPA national estimates (Table 1.2) have a number of shortcomings, such as the lack of national C&D waste composition estimates made in either of the US national estimates.

Table 1.2 Summary of estimated amount of building-related C&D materials generated in US.

Year	Residential			Non Residential			Publication
	Construction (million tons)	Renovation (million tons)	Demolition (million tons)	Construction (million tons)	Renovation (million tons)	Demolition (million tons)	
1996	6.6	31.9	19.7	4.3	28.0	45.1	Franklin Associates 1998
2003	10.0	37.5	19.0	5.0	29.0	65.0	US EPA 2009a

In the place of a national C&D waste composition estimate, Franklin Associates 1998 cites the regional composition estimates from six studies, whereas the US EPA 2009a study does not contain any regional composition estimates. In Franklin Associates 1998, the primary reason for not averaging the six regional C&D waste composition studies to produce a national estimate was that C&D waste samples were collected under many different conditions and levels of detail, as seen in the variety of C&D materials classifications used in Table 1.3 (Franklin Associates 1998).

Table 1.3 Comparison of C&D waste material classifications used in composition studies cited in Franklin Associates 1998.

	Composition Study 1	Composition Study 2	Composition Study 3	Composition Study 4	Composition Study 5	Composition Study 6
C&D Material Classifications Used	Asphalt	Cardboard	Glass	Asphalt	Asphalt	Asphalt
	Brick	Concrete	Hazardous Waste	Brick	Brick	Brick
	Concrete	Drywall	Metals	Carpeting	Cardboard	Concrete
	Drywall	Metal	Mineral Aggregates	Cinder Block	Concrete	Landfill Debris
	Fiberglass	Miscellaneous	Other Materials	Concrete with Rebar	Drywall	Roofing
	Glass	Roofing	Other Organics	Concrete without Rebar	Metal	Scrap Iron
	Inerts	Wood	Paper	Corrugated	Other	Wood
	Masonry and Tile		Plastics	Dirt/Earth	Plastic	
	Metals		Wood Waste	Drywall	Roofing	
	Mixed		Yard Wastes	Electrical Fixtures	Wood	
	OCC			Electrical Wiring		
	Other mixed C&D			Furniture		
	Other Packaging			Glass		
	Other Roofing			Insulation-Foam		
	Plastics and foam			Insulation-Sheathing		
	Shingles			Masonite/Slate		
	Textiles			Metal Drums		
	Wood			Metal-Ferrous		
				Metal-Nonferrous		
				Misc. Fines		
				Other Paper		
				Pallets		
				Plastic Film		
				Plastic-PVC Pipe, Rigid, etc.		
				Pressboard/Chipboard		
				Porcel/Bathrm Fixtures		
				Roofing Material-Felt		
				Roofing Material-Shingles		
				Rubber		
				Siding-Aluminum		
				Siding-Vinyl		
				Textiles		
				Tile/Ceramics		
				Tile-Ceiling		
				Tires		
				Treated Wood		
				Tree Limbs/Stumps		
				Untreated Wd.-Dimen.Wd.(not paint.)		
				Untreated Wd.-Plywood		
				Untreated.Wd.-Dimen.Wd.(paint.)		
				White Goods/Appliances		

One outcome of the uncertainty and estimate shortcomings of current national C&D waste flow publications (Table 1.2) is that the estimates of C&D waste flows are only useful for gaining a general 'snapshot' (Franklin Associates 1998, US EPA 2009a). Using these estimates in further uses must also be considered general 'snapshots' since these estimates lack certainty and specificity of the quality, quantity, location and time of C&D waste emission to claim otherwise. This is a major concern as one of the most common reasons for estimating C&D waste flows and their diversion rates is to inform materials recovery programs (Franklin 1998, US EPA 2009a).

As a result of these 'snapshot' national C&D waste flow estimates, current diversion estimates lack important composition details and certainty in their figures. For instance, in 2003 it was estimated that 81 million tons or 48% of C&D wastes were diverted (US EPA 2009a). However, little else is know of this estimate as the material composition, contributing sectors and materials having the largest influence on the recovery rates could not be determined (US EPA 2009a). Furthermore, the estimated US average diversion rate of 48% was extrapolated from a sample of 8 states, where different diversion estimation methods were being used and diversion rates ranged from 1% to 80% (US EPA 2009a). Lastly, this estimate is significantly different from a diversion estimate derived from a 2004 C&D waste diversion survey carried out by the Construction Materials Recycling Association (CMRA). Figures derived from the CMRA survey estimated that 28 million tons or 16% of C&D wastes were diverted from landfill in 2004 which is significantly lower than the 2003 estimate of 81 million tons or 48% estimated by the US EPA (US EPA 2009a). The high levels of uncertainty and lack of composition information in current estimates of C&D waste flows are cited clearly within each report and each estimate should only be considered as a 'snapshot' of potential national diverted C&D wastes for the US. It would be highly speculative and risky to utilize this estimate in the decision making of national material recovery programs.

Despite the lack of certainty in the composition of C&D wastes being emitted and diverted from the US construction sector, it has been generally estimated that concrete/rubble, wood and drywall represent the largest contributions to C&D wastes (Franklin Associate 1998, Sandler 2003). A search for literature containing national estimates on each of these three C&D waste flows revealed only sources for C&D wood waste flows (Table 1.4).

Table 1.4 Summary of national US construction industry C&D wood waste flow estimates.

	Wood Construction Waste			Wood Demolition Waste			
	Published Estimates			Published Estimates			
	Single Family	Residential (SF +MF)	Residential and Nonresidential	Single Family	Residential (SF+MF)	Residential and Nonresidential	
Year	(million tons)	(million tons)	(million tons)	(million tons)	(million tons)	(million tons)	Publication
1990			10.3			24.4	McKeever 1999
1991			9.1			24.6	McKeever 1999
1992			9.1			24.9	McKeever 1999
1993	2.5		9.5		23.0	25.2	Ince and McKeever 1995, McKeever 1999
1994			9.5			25.4	McKeever 1999
1995			8.6			25.7	McKeever 1999
1996			8.8			25.9	McKeever 1999
1997			8.6			26.2	McKeever 1999
1998		3.4, 3.6	8.7		6.8	26.4	McKeever 1999, Sandler 2003, McKeever 1999
2002	3.4						McKeever 2004

These national US construction industry C&D wood waste flow estimates represent the highest quality estimates for any single generic C&D waste flow material category. Despite this, these generic estimates of C&D wood waste flows also suffer from significant uncertainty and estimate shortcomings, which will be addressed in the first and second papers in this thesis.

If a major reason for estimating the US construction sector's C&D waste flows is to increase the diversion of wastes from the landfill by providing insightful information, then improvements must be made to overcome the uncertainty and shortcomings of current C&D waste flow estimates as they are currently able to serve these purposes (Franklin 1998, US EPA 2009a).

1.4 Conclusion

There is a clear need to reduce the landfilling of C&D waste emitted from the US construction sector's activities. This has resulted in an increase in demand for the services of C&D waste product recovery markets to increase their diversion of C&D wastes from landfills. However, this market would benefit from complete C&D waste flow information to freely explore the wants and uses of C&D waste products and rationally guided its operations, as well as develop value-adding strategies in order to competitively and economically divert wastes from the landfill. Thus, complete information on C&D waste flows emitted from the US construction sector are required to support the optimal development of a complementary C&D waste product recovery market.

The few existing estimates of national C&D waste flows and their diversion from landfills do not meet the needs of the C&D waste product recovery market and are considered as barriers to its optimal development. One of the main challenges in attaining high quality and complete C&D waste product information is the challenge of collecting high quality empirical data to capture the broad range of variations in quantity, quality, location and timing of C&D waste product emissions. This thesis draws on the recommendation to overcome these challenges in order to improve upon the current information and support the development of the C&D waste product recovery market through two manuscript chapters. The challenges faced in collecting high quality C&D waste flow empirical data are addressed in the second chapter, and the third chapter focuses on developing product specific estimates to contrast with the generic C&D waste flows currently available in literature.

The second chapter, entitled *Developing the Reuse and Recycling Market: Improving Empirical Data Collection Methods to Increase the Applicability of US C&D Waste Estimates*, addresses the high levels of uncertainty and significant methodological shortfalls of the current US EPA national C&D waste estimates. It follows this address with a suggested framework of improvements that apply to the collection methods used and resolution of empirical data collected. In order to resolve the issue of lacking information for C&D waste product recovery firms to explore value-adding opportunities in the market, estimates must be based on high quality data with high resolution for the information on C&D waste flows.

The third chapter, entitled *Determining Stocks and Flows of Structural Wood Products in Single Family Homes in the United Stated*, focuses on developing a national stocks and flows model for structural wood product use in single family residences in the US between 1950 and 2008, thereby providing important data on a key sector of the construction industry's activities. This stocks and flows model focuses on single family homes and structural wood product consumption in the US construction sector was entirely due to the areas of structural wood products and single family homes having the largest amount of high quality information available (McKeever 2009).

These two chapters contain respective literature reviews and are structured to be read as stand alone papers.

1.5 Works Cited

Alchian, A. 1950. Uncertainty, Evolution, and Economic Theory. Journal of Political Economy. 58(3):211-221.

Barney, J. 1986. Strategic factor markets: Expectations, luck, and business strategy. Management Science. 32(10):1231-1241.

Brunner, P. and H. Rechberger. 2002. Anthropogenic Metabolism and Environmental Legacies: Causes and Consequences of Global Environmental Change (Vol. 3). John Wiley and Sons, Ltd. Chichester, England. pp 54-72.

Cachon, G.P. and M. Fisher. 2000. Supply chain inventory management and the value of shared information. Management Science. 46(8):1032-1048.

Cheyne, I., and M. Purdue. 1995. Fitting definition to purpose: The search for a satisfactory definition of waste. Journal of Environmental Law. 7(2):149-168.

CIWMB. 2004. Barriers to C&D reuse and recycling. California Integrated Waste Management Board. http://www.calrecycle.ca.gov/archive/IWMBMtgDocs/mtgdocs/2005/03/00018124.ppt (Accessed 1 Aug 10.)

Cochrane, K., Dubey, B., Henry, S. and T. Townsend. 2007. Government policies for increasing the recycling of construction and demolition debris. Clay County Solid Waste Division. Florida Department of Environmental Protection. pp 18.

Dierickx, I. and K. Cool. 1989. Asset stock accumulation and sustainability of competitive advantage. Management Science. 35(12):1504-1511.

Fleischmann, M., Bloemhof-Ruwaard, J., Dekker, R., van der Laan, E., van Nunen, J. and L. Wassenhove. 1997. Quantitative models for reverse logistics: A review. European Journal of Operational Research. 103(1):1-17.

Franklin Associates. 1998. Characterization of building-related construction and demolition debris in the United States, June 1998. US Environmental Protection Agency. Municipal and Industrial Solid Waste Division. Office of Solid Waste. EPA530-R-98-010. Washington, DC.

Hawken, P. 1993. The ecology of commerce: A declaration of sustainability. Harper Collins Publishers. New York, NY. pp 250.

Horvath, A. 2004. Construction materials and the environment. The Annual Review of Environment and Resources. 29:181-204.

Ince, P. J. and D.B. McKeever. 1995. Recovery of paper and wood for recycling: Actual and potential. General Technical Report FPL-GTR-88. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 13 pp.

Ives, G. and G. Learmonth. 1984. Information as a competitive weapon. Communications of the ACM: Special section on management of information systems. 27(12):1193-1201.

Mancke, R. 1974. Causes of interfirm profitability differences: A new interpretation of the evidence. Quart. Journal of Economics. 88(2):181-193.

McKeever, D.B. 1999. Changes in the US Solid Waste Wood Resource, 1990 to 1998. US Department of Agriculture, Forest Products Laboratory, Madison, WI. 14 pp.

McKeever, D.B. 2004. Inventories of woody residue and solid wood waste in the United States, 2002. US Department of Agriculture, Forest Products Laboratory, Madison, WI. 16 pp.

McKeever, D.B. 2009. Estimated annual timber products consumption in major end uses in the United States, 1950-2006. General Technical Report FPL-GTR-181. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 47 pp.

Mowery, D. and N. Rosenberg. 1979. The influence of demand upon innovation: A critical review of some recent empirical studies. Research Policy. 8(2):102-153.

Pohlen, T.L. and M. Farris II. 1992. Reverse logistics in plastic recycling. International Journal of Physical Distribution and Logistics Management. 22(7):35-47.

RocSearch Ltd. (2005). US Construction Sector: An Analysis. Pub ID: ROCS1185267. 45 pp.

Rumelt, R. 1984. Towards strategic theory of the firm. Robert Lamb (ed.) Competitive Strategic Management. Englewood Cliffs, NJ: Prentice Hall. pp. 556-570.

Sandler, K. (2003). Survey statistics: Analyzing what's recyclable in C&D debris. BioCycle. 44(11):51-54.

Tchnobanoglous, G., Thiesen, H. and S. Vigil. 1993. Integrated Solid Waste Management: Engineering Principles and Management Issues. McGraw-Hill, New York, NY. 978 pp.

US EPA. 2009a. Estimating 2003 building-related construction and demolition material amounts. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-002. Washington, DC. 60 pp.

US EPA. 2009b. "Green Servicizing" for a more sustainable US economy: Key concepts, tools and analyses to inform policy engagement. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-006. Washington, DC. pp 129.

2 Developing the Reuse and Recycling Market: Improving Empirical Data Collection Methods to Increase the Applicability of US C&D Waste Estimates

2.1 Introduction

Material flow information is required in order to more effectively quantify and address how economic activities are impacting the environment (National Academy, 2004). Demand for this information is growing rapidly due to an increasing global consensus on the need to develop sustainable economic infrastructures (APEC 2009, OECD 2009, SETAC 2009, UNEP 2009, World Bank 2001). The United States (US) is currently working on aligning economic success and environmental stewardship through creating policies to support business models that provide necessary goods and services with reduced energy, material, and water use (US EPA 2009b). As this effort seeks to address complete life cycles (ie. cradle-to-grave), strong waste flow information intelligence will be one of the keys to informing and tracking the success of the policies and business models pursued by the United States Environmental Protection Agency (US EPA).

One method to reduce material usage while also creating economic benefits is diverting waste from the landfilling into reuse and recycling (R&R) activities through waste product recovery markets (US EPA 2009a). The operations of this market diverts wastes into further utility deriving markets, which in turn reduces the demand for virgin resources and process energy. This market also saves waste emitters dumping fee expenses and creates comparatively more jobs than a scenario where wastes are dumped (US EPA 2009b). A further benefit of the waste product recovery market's operations is the avoidance of unnecessary occupation of landfill space where potentially harmful leachates and off-gassing may occur (Federle 1993).

The availability of high quality waste flow information detailing trends in quantity, quality and emission locations over time is important to consider in the development of waste product recovery market operations, as they require certainty of supply to rationally guide their business strategy (Pohlen and Farris 1992, Fleischmann et al. 1997). Furthermore, this market would also benefit from supporting policy infrastructures, informed with the same high quality waste flow information, that help it optimize it's position to economically divert increasing amounts of waste flows. Unfortunately, in many cases such information on waste flows resulting from economic activity is unavailable, presenting a barrier to the optimal development of waste product recovery markets.

Despite being one of the largest consumers of materials (Horvath, 2004) and producers of wastes in North America (Franklin Associates 1998, US EPA 2009a), the United States (US) construction sector does not yet have detailed and accurate information on it's C&D material waste flows. In addition to this, there is also a lack of knowledge on the broad impacts created by disposing of this sector's waste (Laquatra 2004, Roussat et al. 2007, CIWMB 2008, Skog 2008). Very few publications have generated estimates to address the spectrum of C&D waste generated by the US construction sector (Franklin Associates 1998, US EPA 2009a). However, these national estimates all contain high levels of uncertainty and suffer from significant shortfalls that reduce their applicability to inform the development of C&D waste product recovery markets.

This lack of C&D waste flow information needs to be addressed in order to optimize the development of a complementary C&D waste product recovery markets for the US construction sector to reduce it's material usage. The purpose of this paper is to identify the shortfalls and uncertainties contained in current national C&D waste flow estimates and detail improvements in the collection and resolution of empirical data.

National C&D waste flow publications currently indicate that the barriers to increased recovery rates are primarily related to the cost of collecting, sorting and processing low value recyclable materials in relation to the cost of virgin materials, low cost of landfilling C&D wastes, buildings and building products that are not designed for recovery, lack of recovery facilities, a lack of defined markets and supporting regulations (Franklin Associates 1998, US EPA 2009a). This paper suggests that making high quality information on the trends in quantity, quality, location and timing of C&D waste flow emissions available would help reduce these barriers as it enables C&D waste product recovery markets to explore market opportunities, rationally guide decision making, develop competitive value-adding strategies, and plan operations (Mowery and Rosenburg 1979, Pohlen and Farris 1992, Tchobanoglous et al. 1993, Peng et al 1997, Fleishmann et al. 1997, CIWMB, 2004).

This paper begins by reviewing the data collection methods of current national C&D waste publications. Recommendations are then made to improve empirical data collection in order to address uncertainties and increase the resolution of national C&D waste flow estimates. These recommendations would help generate higher quality national C&D waste flow estimates capable of effectively supporting the optimal development of C&D waste product recovery markets to complement the C&D waste flows emitted from the US construction sector's activities.

2.2 Current C&D Publications

Developing a profile of available C&D waste flows (eg. quality, quantity, location of emission) would enhance the accuracy of assessments regarding their recovery and reuse as resources (Franklin Associates 1998, McKeever 1999, Falk and McKeever 2004, US EPA 2009a). Publications that estimate national C&D waste flows in the US have had to develop unique estimation methods to compensate for the general lack of information on this topic (Ince and McKeever 1995, Franklin Associates 1998, Falk and McKeever 2004, McKeever 2004, US EPA 2009a). Estimation methods used generally consist of two activities; the collection of empirical data and the extrapolation of collected data to estimate national C&D waste flow information. Although publications suffer from uncertainties and shortcomings originating in each of these two activities, this paper focuses on those issues that can be mitigated at the collection of empirical C&D waste flow data, as estimated information can only be as accurate as the data that it is based upon.

This paper proposes the collection of data on the full spectrum of C&D waste flows emitted from the US construction sector, thus it focuses on reviewing publications that report on all construction products used by the US construction sector. There are only two known US national C&D waste flow publications that fulfill this requirement; Franklin Associates 1998 and US EPA 2009a. Since the US EPA 2009a publication estimated 2003 C&D waste flows to update the Franklin Associates 1998 values using the same methods and the majority of the same empirical data, this paper's commentary on current publications will focus on Franklin Associates 1998.

The uncertainties and shortcomings of the Franklin Associates 1998 C&D waste flow estimates are addressed in the following section.

2.2.1 Methods for Estimating National C&D Waste Flows

The C&D waste flow estimations in Franklin Associates 1998 are the result of multi-state and multi-stakeholder collaborations to quantify and characterize construction, renovation and demolition waste flows arising from the US construction sector. These collaborations were necessary to collect empirical data due to the lack of available information on C&D waste flows in the US. As a result the main body of work consisted of sampling C&D waste flows resulting from individual building construction activities. This collected data was used to extrapolate estimations of national C&D waste flows resulting from US construction activity.

A review of Franklin Associates 1998 was carried out in order to address the considerable uncertainties acknowledged in the published C&D waste flow estimates. This review revealed both sources of uncertainty as well as estimate shortcomings originating at the collection of empirical C&D waste flow data, which are addressed in the following sections.

2.2.1.1 Sources of Uncertainty

The sources of uncertainty in data collection were found to be caused by the lack of standardized collection methods and the small sample of buildings from which data were collected.

Although the Franklin Associates 1998 study involved many different organizations, there was not a uniform set of standards used for the collection and storage of sampled waste materials. Consequently, waste samples were collected under a wide range of conditions and at various levels of detail (Franklin Associates 1998). Without a standardized collection method, there is concern over uncertainty created by aggregating the collected data.

There are a number of sources of uncertainty relating to the sample size of buildings considered in the Franklin Associates 1998 publication. As seen in Table 2.1, the largest sample size taken as a percentage of the national estimate extrapolated from it was 0.043% for non-residential demolition waste flows.

Table 2.1 Franklin Associates C&D waste sample sizes used to extrapolate US national estimates.

(Franklin Associates 1998)

	Residential (single and multi family)			Non-Residential (various)		
	Sample Size		Extrapolated National Estimate ('000 Tons)	Sample Size		Extrapolated National Estimate ('000 Tons)
Construction Activity	('000 Tons)	(% of National Estimate)		('000 Tons)	(% of National Estimate)	
Construction	0.38	6.0×10^{-3}	6,560.00	0.76	1.8×10^{-4}	4,270.00
Renovation	0.03	9.4×10^{-5}	31,900.00	-	0	28,000.00
Demolition	0.31	1.6×10^{-3}	19,700.00	192.61	4.3×10^{-2}	451,000.00

In addition to low sample sizes, there are also representative sampling issues within residential and non-residential building types in the US. For instance, only single family homes were sampled to represent residential renovation waste flows. There were also no waste flows sampled for non-residential renovation waste, which resulted in its waste flow rate being assumed to by the residential renovation's waste flow rate. For residential demolition waste flows, none of the sampled building's structures included a basement. In order to compensate for this, figures characterizing waste flows resulting from a full basement were estimated.

For non-residential demolitions, the number of buildings demolished in 1996 was assumed to be the same as the number of buildings demolished in 1994. Lastly, Franklin Associate 1998 does not characterize a national composition of building-related C&D wastes generated in the US, despite this being one of its primary purposes. Although there are point source sampling studies cited, disparities in their data collection conditions and levels of detail made their aggregation into a national estimate not possible. Furthermore, these studies were insufficient to represent national waste flows as they were geographically biased to six regions (Figure 2.1), with no sampling of southern US buildings.

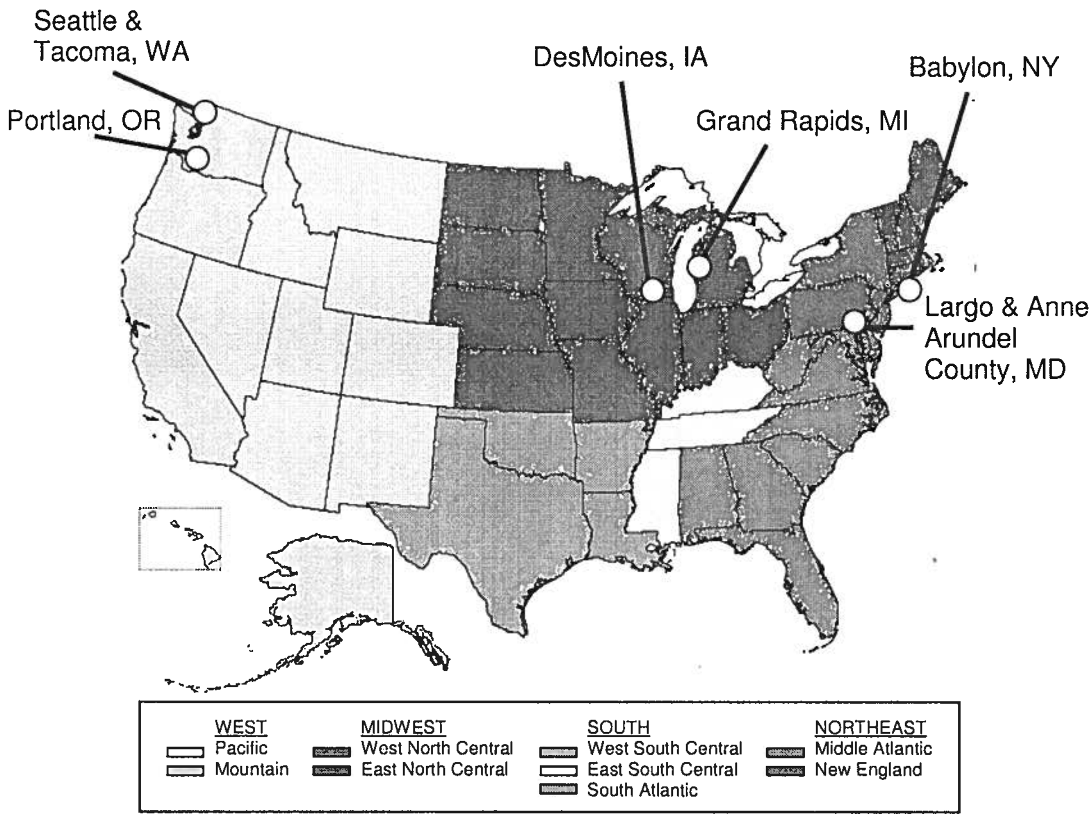

Figure 2.1 Locations of empirical C&D composition data collection in Franklin Associates, 1998.

As illustrated in this section, the lack of standardized collection methods and the small sample of buildings from which data were collected created sources uncertainty in the Franklin 1998 C&D waste estimates.

2.2.1.2 Estimate Shortcomings

In addition to causing uncertainties, the lack of detail in data collected caused two types of major shortcomings in the C&D waste flow estimates in Franklin Associates 1998. A low resolution in the data and temporal limitations of the data make it impossible to discern C&D construction product waste types, sources and trends. With regards to product waste types, all but one of the composition studies cited express C&D construction product wastes by their generic material groups (eg. concrete, wood, metals) rather than estimating by their product names (eg. softwood lumber, aluminum siding, asphalt shingles).

Furthermore, all non-residential wastes were not differentiated by their respective sources (eg. private industrial, office, hotels/motels, commercial, religious, educational, hospital and institutional, public industrial), as they were aggregated and reported as a single building type. The same occurred with respect to renovation wastes as they were reported as a single waste type rather than being differentiated to accurately represent the respective renovation sources (eg. kitchen, bathroom and house remodeling, room addition, roof and cladding replacement) and waste types (eg. renovation construction waste or renovation demolition waste) contributing to this waste flow. Lastly, Franklin Associates 1998 is temporally limited to estimating C&D waste flows for a single year, 1996, whereas multi-year estimates would reveal valuable information on waste flow trends. Multi-year estimates indicating waste flow trends would be another extremely valuable asset to C&D waste product recovery markets as it would facilitate forecasting the availability and characteristics of C&D wastes.

Despite these uncertainties and estimate shortcomings, the Franklin Associates 1998 study remains the most comprehensive assessment of US building related C&D waste flows as it's estimates have been cited and incorporated into numerous subsequent publications (Dantata et al. 2004, Haselbach and Bruner 2006, Kofoworola and Gheewala 2009, Laefer and Manke 2008, US EPA 2009a, Wang et al. 2004, Webster 2004) and on public webpages (CalRecycle 2010, New Rules Project 2010, Recycle C&D Debris 2010). The extensive use of this single study emphasizes the demand for C&D waste flow information, despite the knowledge that the estimates obtained to date are highly uncertain and do not contain all relevant waste flow details.

The sources of uncertainty and estimate shortcomings identified above should be addressed in order to increase the applicability of national C&D waste flow estimates and support the development of C&D waste product recovery markets. The following section details recommended empirical data collection improvements to the method of collection and resolution of empirical data.

2.3 Recommended Empirical Data Collection Improvements

This section addresses the identified sources of uncertainty and estimation shortcomings of Franklin Associates 1998 with a framework of suggested improvements that apply to the collection methods used and resolution of empirical data collected. The aim of this framework is to provide more appropriate information with which to support the optimal development of C&D waste product recovery markets to complement the US construction sector. Recommended improvements include:

- Methods of empirical data collection
  - Measurement at the construction site.
  - Standardization of reporting.
- Empirical data resolution
  - Differentiation of renovation construction and renovation demolition wastes.
  - Accounting for construction materials stocked into buildings.
  - Characterization of construction materials at the product level.
  - Implementation of regulatory mechanisms.

The details of how these recommendations address the sources of uncertainty and estimate shortcomings in Franklin Associates 1998 are presented in the following sections.

2.3.1 Methods of Empirical Data Collection

The following sections outline suggestions to address the sources of uncertainty caused by a lack of standardized protocols for empirical data collection in the Franklin Associates 1998 publication.

2.3.1.1 Measurement at the Construction Site

As construction and demolition waste flows occur at each construction phase of a building's life cycle it is suggested that they be measured on site at the point of emission. Figure 2.2 was developed to illustrate the physical relationship between construction material flows (italicized), construction activities (circled), and the temporary stock of construction materials into a building's structure (in square). For a given building, each of the construction activities (Figure 2.2) are carried out at its construction site. Thus, accounting for C&D waste flows at the construction site when material flows are created by construction activity would accurately maintain an account of C&D waste flows being emitted from a given construction site.

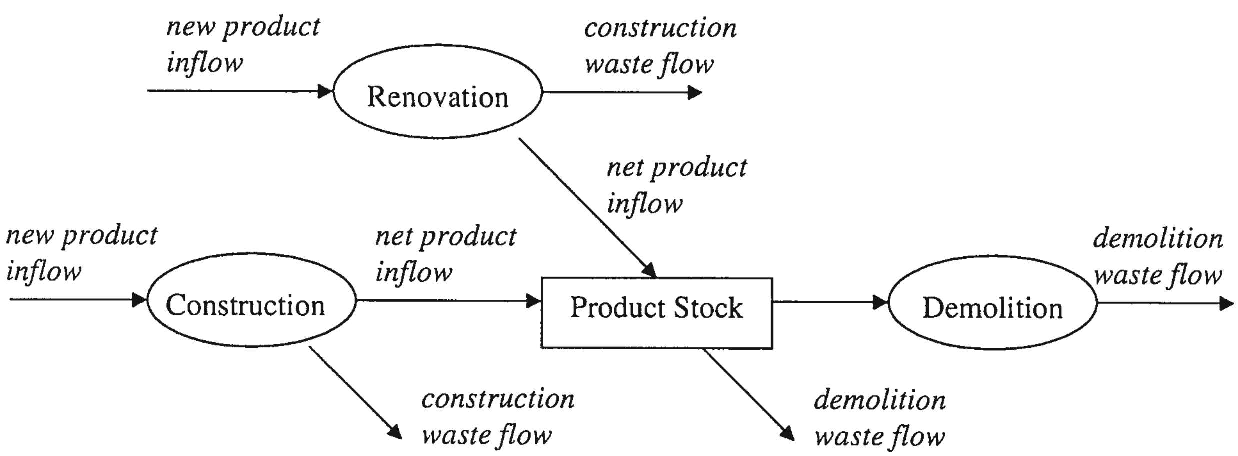

Figure 2.2 Product and waste flows occurring during a building's life cycle.

The construction site is the most accurate point for quantifying C&D waste flows as C&D wastes may disperse to differing end-of-life scenarios (eg. to landfill, recycling, reuse or become contaminated due to mixing with other wastes upon leaving a construction site) (Sandler 2003). This source of uncertainty is not unique to the Franklin Associates 1998 publication, as sorting at the construction site was also a source of error in the Ince and McKeever 1995 study, where wood wastes were overestimated due to the use of sampling at the landfill. Furthermore, requiring measurement of waste flow data by those directly involved in a given building's on-site construction activities (eg. contractors and developers) is also preferable as it can be a challenge to obtain permission to collect this data at private landfills (Franklin Associates, 1998). Gaining the cooperation of those directly involved in construction activities will require careful consideration of construction activity operations and their constraints (ie. time and budget). This paper addresses the potential source of uncertainty caused by varying sampling location by recommending that waste flows are measured at the construction site, when they are in their least contaminated and most accessible form.

2.3.1.2 Standardization of Reporting

To address the uncertainty that restricted the comparability of composition studies cited in Franklin Associates 1998, it is recommended that a standardized reporting protocol be incorporated to collect information on the full life cycle of individual buildings. This data reporting protocol consists of using standardized input documents to record data (eg. new product inflow, net product inflow, construction waste flow, demolition waste flow) at the subsequent construction stages (eg. construction, renovation, demolition) throughout the building's life cycle (Figure 2.3). In this thesis the activities occurring in each subsequent construction stage are defined as follows; the construction stage includes the initial creation of a building through the assembly of construction products, the renovation stage includes the remodeling, replacements, repairs, and additions, and the demolition stage is the end of life of a building where it is wholly demolished or disassembled. These documents would significantly enhance comparability among collected C&D waste flow data within and between collection sites. A conceptual example is presented in Figure 2.3, which references elements from Figure 2.2. In Figure 2.3 the ellipses indicate subsequent input documents that are completed or updated when further renovation activities occur.

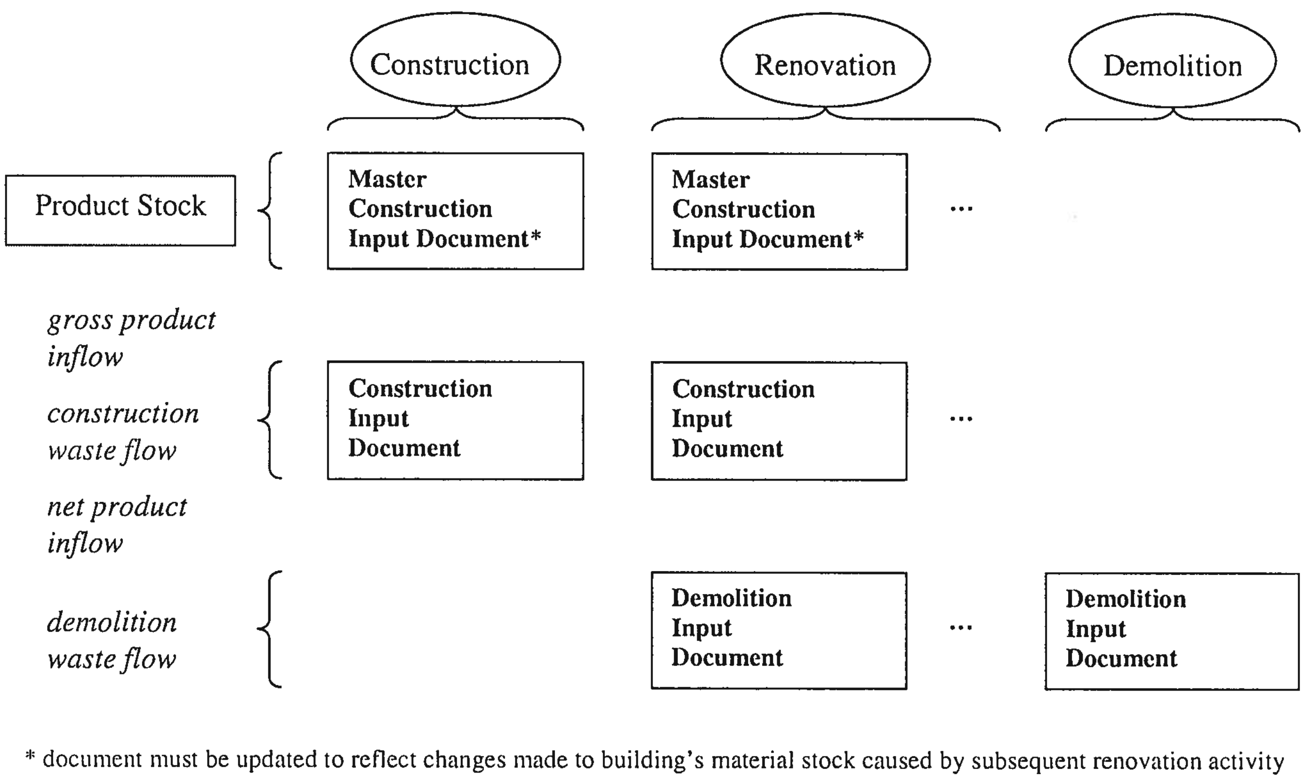

Figure 2.3 Input documents to be completed and/or updated at each respective construction activity.

The input documents presented in Figure 2.3 contain descriptive data that quantify all material flows resulting from each construction activity. The data they record and it's direct uses are explained below.

- The **Master Construction Input Document** maintains a record of the building's product stock throughout its life cycle, taking into account net changes due to renovation activities. This document would also forecast end-of-life *demolition waste flows.*
- The **Construction Input Document** provides data on *gross product inflow*, *construction waste flow* and *net product inflow* resulting from respective construction and renovation activities. This provides the data for creating and updating the Master Construction Input Document, as a Construction Input Document must be completed whenever construction or renovation activity occurs on the building.
- The **Demolition Input Documents** provide a summary of the *demolition waste flows* resulting from renovation and demolition activities. When renovating, this would be used to update the Master Construction Input Document. At the building's end-of-life, the Demolition Input Document would equate with the Master Construction Input Document, as all products contained in the building would be categorized as *demolition waste flows.*

In addition to documenting those stocks and flows resulting from on-site construction activities, the location that C&D waste flows are disposed of or diverted to must be described in order to determine the proportions of products that were disposed of in landfills, incinerated, recycled or reused. This documentation will complement the C&D empirical data collection by providing further insight into waste treatment trends, C&D waste product recovery market activity and the success of C&D diversion efforts. Methods for accomplishing this documentation will vary depending on what is available in the region where wastes were produced. For instance, there may be certified waste handlers that can produce certified weight tags, such as in the San Diego Construction and Demolition Debris Diversion Deposit (CDDDD) program (City of San Diego 2007). If there are no certified waste handlers, other verification mechanisms may be used, such as waste hauling forms. It is recommended that the waste hauling form includes the contact information of those individuals involved in the transaction in addition to the suggested stock and flow data so that all data collected may be validated upon further investigation.

The use of standardized measurement at point of emission and data reporting protocols are recommended in order to address the uncertainty cause by the collection methods used seen in previous studies.

2.3.2 Empirical Data Resolution

The following sections address the C&D waste flow estimate shortcomings caused by low resolution and temporal limitations in the Franklin Associates 1998 publication, as well as the sources of uncertainty caused by low sample sizes and incomplete geographic coverage used extrapolate the C&D waste flow estimates.

2.3.2.1 Differentiation of Renovation Construction and Renovation Demolition Wastes

As there are two distinct waste flows emitted during renovation activities (eg. construction and demolition wastes) (Figure 2.2), reporting wastes emitted from renovation generically as 'renovation waste' does not provide adequate information resolution about the waste flows for firms seeking to identify recycling reuse opportunities (Franklin Associates 1998, SWANA 2002, US EPA 2009a). Construction wastes typically consist of trim scraps as a result of sizing construction materials and are more readily sorted. In contrast, demolition wastes are typically a mass of construction materials of various qualities that are comingled, contaminated and/or fastened together (Franklin Associates 1998). This paper recommends reporting 'renovation waste' by its respective waste types (eg. renovation construction and renovation demolition wastes) in order to better inform C&D waste product recovery markets. Differentiating between renovation construction and renovation demolition wastes will increase the resolution of data collected by maintaining an accurate description of waste flows and activities from which they arise. Providing C&D waste product recovery markets with more accurate information on the sources and availability of C&D wastes will improve their ability to identify, evaluate and position themselves to take advantage of market opportunities (SWANA 2002).

2.3.2.2 Accounting for Construction Materials Stocked into Buildings

The collection of data with a resolution that includes all construction materials stocked into building structures is also important to consider in the development of the C&D waste product recovery market as this data would be useful in producing information, such as C&D waste flow forecasting. This data is useful in a variety of other important applications, such as estimating the phase-out of hazardous construction products from the building stock (Jambeck et al. 2007) and the amount of carbon sequestered into building structures (Wilson 2006). For these important reasons, this paper recommends that construction product waste flow data be accompanied by the collection of *net product inflows* and product stocks (Figure 2.2).

2.3.2.3 Characterization of Construction Materials at the Product Level

This paper recommends collecting construction material data with a product level resolution, as all C&D waste flows do not have the same reuse and recycling potential. A few publications have estimated C&D wood waste flows in order to identify the potential for wood waste product recovery markets (Ince and McKeever 1995, McKeever 1999, Falk and McKeever 2004). However, a major shortcoming of each study is that they do not provide adequate information on wood waste flows to enable C&D waste product recovery markets to evaluate and strategically position their operations. For instance, firms seeking to reuse wood value solid wood products differently than engineered wood products (EWPs) and treated wood products (US EPA 2009a). Furthermore, the presence of contaminants in EWPs (eg. resins and waxes) and treated wood products (eg. chromated copper arsenate (CCA)) requires different operational consideration such as handling techniques in various recycling scenarios (Shupe and Hse 2003, Lennon 2005). Further considerations, EWPs behave differently in the landfill when compared to solid wood products due to the presence of contaminants (Peltola et al. 2000). As various compositions exist within the various generic material groups, such as concrete, wood and metals, it would be beneficial to obtain detailed C&D waste flows at the product level in order to be able to consider and accurately evaluate appropriate reuse and recycling opportunities.

As a conceptual example for the generic material category of wood, the suggested product level of C&D waste flow detail would be to collect are presented below. In this example for wood, it should also be noted that further details such as wood species and finish type would increase the product level resolution.

Wood construction products;

- softwood lumber
- softwood plywood
- oriented strandboard (OSB)
- glue laminated timbers (Glulam)
- I-joists
- laminated veneer lumber (LVL)
- finger-jointed lumber
- treated lumber
- hardwood lumber
- medium density fiberboard (MDF)
- particleboard
- hardboard

The specification of construction products at the design phase of a building presents a significant opportunity to document empirical data on stocked and wasted construction products according to material specification standards. By using existing material specification standards, such as MasterFormat, pre-existing naming standards can be used. This will increase comparability of data collected as a standardized nomenclature would to produce comparable empirical data across different building sites and legislative jurisdictions, as well as to maintain detail when collected data are aggregated in a database which will increase comparability. Furthermore, a direct link is created to databases containing further details of the construction products (Bertram 2005). This would be the ideal method to access a rich construction product information resource and attain a high resolution in empirical data collected on stock and C&D waste flows.

Collecting empirical data on the respective construction products within each material category would significantly increase the resolution of C&D waste flows.

2.3.2.4 Implementation of Regulatory Mechanisms

In order to address the uncertainties caused by low sample sizes and publication shortcomings due to temporal limitations, the use of regulatory mechanisms is one means of encouraging the construction industry to regularly collect important C&D data.

Individual construction projects are regulated by existing building codes and regulations, which are enforced at the regional level (eg. counties in the US). These existing regulatory organizations are possible candidates to become involved in the development of a data collection system for C&D waste flows. To encourage data collection, this paper recommends the use of a deposit/refund policy, as used by the San Diego CDDDD program, where a deposit is taken before the construction activity begins and it is not returned until all of the information required is provided. The CDDDD program applies to building permits and to demolition/removal permits, as per the City of San Diego Municipal Code (City of San Diego 2007). This method of collection is effective at increasing compliance and has the added benefit of potentially raising funds from unclaimed deposits to support the administering organizations efforts

(Cochran et al. 2007). To support this method, the increasing number of construction firms becoming involved in green building activities would also facilitate the implementation of a deposit/refund policy, as this indicates increasing interest in being environmentally conscious while green building programs promote the use of waste management plans (Lennon 2005, USGBC 2005, McGraw-Hill 2008). Involving existing regulatory organizations and implementing a deposit/refund regulatory mechanism will help encourage construction firms to collect data and ensure that data collected adheres to the required collection method standards.

Developing a standard collection methodology is the first step towards increasing the accuracy of national estimates. However, a larger sample size and data collection that includes more details are necessary in order to develop C&D waste product recovery markets to complement the C&D waste flows being emitted by the US construction sector. One way of achieving these goals would be for several participating regions (eg. counties in the US) to apply the same collection standards and resolution requirements. This would create the opportunity to aggregate county data at the state level, and subsequently at the national level (Figure 2.4).

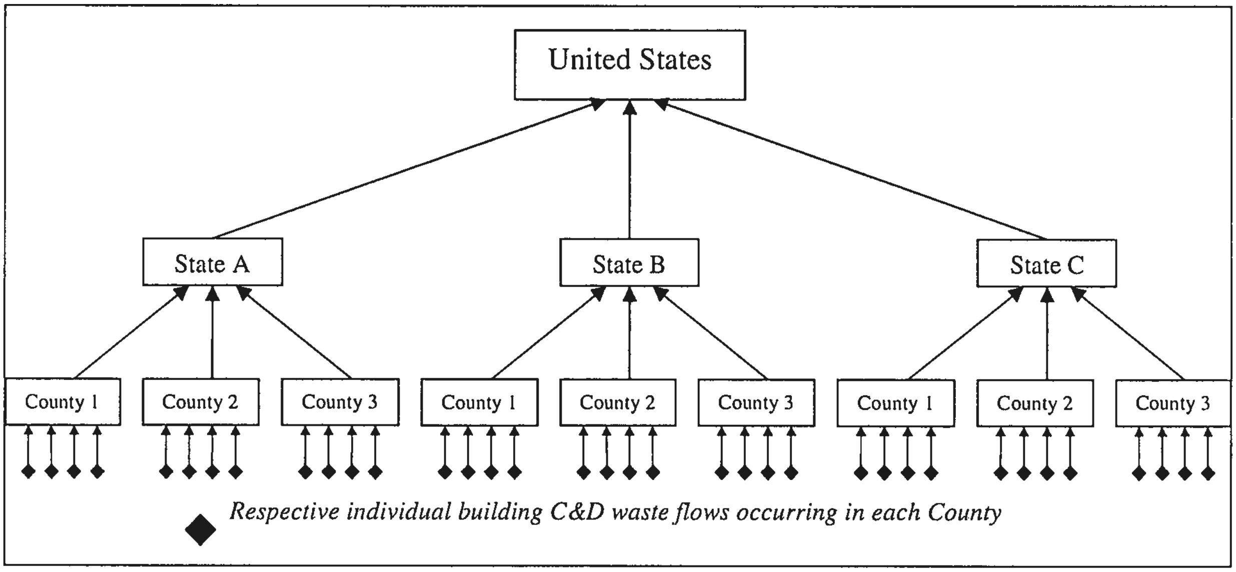

Figure 2.4 Conceptual framework for C&D waste flow data collection and management from the US construction sector.

The framework outlined in Figure 2.4 represents one empirical data collection situation and would require significant buy-in and policy support. Ideally the resulting C&D waste flow information would be made available online through a publicly accessible web portal. This would give free access to high quality and detailed empirical data on C&D waste flows on many geographic and temporal scales in order to support various scales of operational development in the C&D waste product recovery markets.

2.4 Conclusions

The construction sector, one of the largest consumers and producers of waste in North America, presently has inadequate data with which to estimate national C&D waste flows. To date, there have only been two known US national C&D waste flow studies that estimate all C&D waste flows; Franklin Associates 1998 and US EPA 2009a. Of these two, this paper focused on Franklin Associates 1998 as the US EPA 2009a publication built upon the Franklin Associates 1998 estimates using the same methodology. A review of the Franklin Associates 1998 publication revealed sources of uncertainty and publication shortcomings originating from the collection of empirical C&D waste flow data. The main causes of this uncertainty were identified to be the lack of standardized data collection methods and the use of small sample sizes, while the main shortfalls identified included the low resolution and temporal limitations of C&D waste estimates. These shortfalls and uncertainties significantly present a barrier to the optimal development of diversion efforts by the C&D waste product recovery market.

This paper proposed recommended data collection improvements to address the uncertainties and publication shortcomings of the Franklin Associates 1998 C&D characterization study . The recommended improvements included;

- Methods of empirical data collection;
    - Measurement at the construction site
    - Standardization of reporting procedures
- Empirical data resolution;
    - Differentiation of renovation construction and renovation demolition wastes.
    - Accounting for construction materials stocked into buildings.
    - Characterization of construction materials at the product level.
    - Implementation of regulatory mechanisms.

The recommended improvements would significantly reduce uncertainties and shortfalls in current US C&D waste flow estimates and contribute to the optimal development of a complementary C&D waste product recovery market. Such developments should result in the increased sustainable use of materials in the US construction sector and subsequently reduce its environmental impact.

2.5 Recommendations

This paper presents a conceptual framework of recommended improvements to increase the certainty and resolution of national C&D waste flow estimates. The primary recommendation is to continue with this conceptual framework and develop working level solutions that could be integrated into standard construction practices. Integrating empirical data collection into standard practices is essential if accurate, detailed and representative data on C&D waste flows from the construction sector's activities are to be collected. A further recommendation is to assess which government and/or government funded organizations would be responsible for handling collected empirical data, aggregating and reporting data collected. This network of agencies, as presented in Figure 2.4, is an essential element in aggregating and sharing the information collected with the C&D waste product recovery market and other interested groups, such as researchers and policy makers.

2.6 Works Cited

APEC. 2009. 1997 APEC Environment Ministerial Meeting on Sustainable Development. Asia-Pacific Economic Cooperation. http://www.apec.org/apec/ministerial_statements/sectoral_ministerial/environment/1997_environment.html (Accessed 18 Sept 09.)

Bertram, P.R. 2005. Life Cycle Assessment and Sustainability: MasterFormat 04 and LCA. Building Design and Construction. November, 2005. p50-51.

CIWMB. 2008. Construction and demolition recycling: Wallboard (drywall) recycling. California Integrated Waste Management Board. http://www.ciwmb.ca.gov/conDemo/Wallboard (Accessed 5 July 08.)

CalRecycle. 2010. C&D Recycling Plan Process. http://www.calrecycle.ca.gov/LGCentral/Library/Innovations/CnDRecycle/Process.htm (Accessed 6 Jan 10.)

City of San Diego. 2007. Municipal Code Chapter 06, Public Works and Property; Public Improvement and Assessment Proceedings. http://docs.sandiego.gov/municode/MuniCodeChapter06/Ch06Art06Division06.pdf (Accessed 15 Sept 09.)

Cochran, K., Dubey, B., Henry, S. and T. Townsend. 2007. Government policies for increasing the recycling of construction and demolition debris. Clay County Solid Waste Division, September 2007.

Dantata, N., Touran, A. and J. Wang. 2004. An analysis of cost and duration for deconstruction and demolition of residential buildings in Massachusetts. *Resources, Conservation and Recycling.* 44(1):1-15.

Falk, R.H. and D.B.McKeever. 2004. Recovering wood for reuse and recycling: A United States perspective. In, Management of Recovered Wood Recycling, Bioenergy and Other Options. Thessaloniki: University Studio Press. pp. 29-40.

Federle, M.O. 1993. Overview of building construction waste and the potential for materials recycling. Building Research Journal. 2(1):31-7.

Fleischmann, M., Bloemhof-Ruwaard, J., Dekker, R., van der Laan, E., van Nunen, J. and L. Wassenhove. 1997. Quantitative models for reverse logistics: A review. European Journal of Operational Research. 103(1):1-17.

Franklin Associates. 1998. Characterization of building-related construction and demolition debris in the United States, June 1998. US Environmental Protection Agency. Municipal and Industrial Solid Waste Division. Office of Solid Waste. EPA530-R-98-010. Washington, DC.

Haselbach, L.M. and S.U. Bruner. 2006. Determining construction debris recycling dumpster densities. Journal of Green Building. 1(3):139-147.

Horvath, A. 2004. Construction materials and the environment. The Annual Review of Environment and Resources. 29:181-204.

Ince, P. J. and D.B. McKeever. 1995. Recovery of paper and wood for recycling: Actual and potential. General Technical Report FPL-GTR-88. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 13 pp.

Jambeck, J., K. Weitz, H. Solo-Garbriele, T. Townsend and S. Thorneloe. 2007. CCA-treated wood disposed in landfills and life-cycle trade-offs with waste-to-energy and MSW landfill disposal. Waste Management. 27(8):S21-8.

Kofoworola, O.F. and S.H. Gheewala. 2009. Estimation of construction waste generation and management in Thailand. *Waste Management. 29(2)731-738.*

Laefer, D.F. and J.P. Manke. 2008. Building Reuse Assessment for Sustainable Urban Reconstruction. Journal of Construction Engineering and Management. 134(3)217-227.

Laquatra, J. 2004. Waste management at the construction site. A Public-Private Partnership for Advancing Housing Technology. www.pathnet.org/si.asp?id=1069 (Accessed 10 Nov 09.)

Lennon, M. 2005. *Recycling construction and demolition wastes: A guide for architects and contractors.* The Institution Recycling Network. 55 pp.

McGraw-Hill. 2008. *Global Green Building Trends SmartMarket Report.* McGraw-Hill Construction. NewYork, NY. 52 pp.

McKeever, D.B. 1999. Changes in the US Solid Waste Wood Resource, 1990 to 1998. US Department of Agriculture, Forest Products Laboratory, Madison, WI. 14 pp.

National Academy. 2004. *Materials Count: The Case for Material Flows Analysis.* National Academy of Sciences. National Academies Press, Washington DC. 124 pp.

New Rules Project. 2010. Recycling Solid Waste. http://www.newrules.org/environment/rules/recycling-and-solid-waste (Accessed 6 Jan 10.)

OECD. 2009. Recommendation of the Council on Material Flows and Resource Productivity. Organization for Economic Co-operation and Development. http://www.oecd.org/dataoecd/3/63/31571298.pdf (Accessed 18 Sept 09.)

Peng, C., Scorpio, D.E. and C.J. Kibert. 1997. Strategies for successful construction and demolition waste recycling operations. Construction Management and Economics. 15(1):49-58.

Pohlen, T.L. and M. Farris II. 1992. Reverse logistics in plastic recycling. International Journal of Physical Distribution and Logistics Management. 22(7):35-47.

Recycle C&D Debris. 2010. Waste Study: Chapter 2. http://www.recyclecddebris.com/rCDd/Resources/WasteStudy/Chapter02.aspx (Accessed 6 Jan 10.)

Roussat, N., Mehu, J., Abdelghafour, M. and P. Brula. 2007. Leaching behaviour of hazardous demolition waste. Waste Management. 28:2032-2040.

Sandler, K. 2003. Survey Statistics: Analyzing what's recyclable in C&D debris. BioCycle. 44(11):51-54.

SETAC. 2009. About SETAC. Society of Environmental Toxicology and Chemistry. http://www.setac.org/node/1 (Accessed 18 Sept 09.)

Shupe, T.F. and C.Y. Hse. 2003. Recycling of decommissioned CCA-treated wood into value-added engineered wood products. Proceedings from the 3rd Annual Special Waste Conference. Solid Waste Association of North America. New Orleans, Louisiana. December 10-12.

Skog, K. 2008. Sequestration of carbon in harvested wood products from the United States. Forest Products Journal. 58(6):57-72.

SWANA. 2002. Successful approaches to recycling urban wood waste. Solid Waste Association of North America. General Technical Report FPL-GTR-133. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 20 pp.

UNEP. 2009. The Green Economy Initiative. United Nations Environment Programme. http://www.unep.org/greeneconomy (Accessed 18 Sept 09.)

US EPA. 2009a. Estimating 2003 building-related construction and demolition material amounts. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-002. Washington, DC. 60 pp.

US EPA. 2009b. "Green Servicizing" for a more sustainable US economy: Key concepts, tools and analyses to inform policy engagement. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-006. Washington, DC. pp 129.

USGBC. 2005. LEED for New Construction and Major Renovations. US Green Building Council. http://www.usgbc.org/ShowFile.aspx?DocumentID=1095 (Accessed 12 Oct 09.)

Wang, J., Touran, A., Christoforou, C. and F. Hatim. 2004. A systems analysis tool for construction and demolition wastes management. *Waste Management. 24(10):989-997.*

Webster, M.D. 2004. Relevance of Structural Engineers to Sustainable Design of Buildings. *Structural Engineering International. 14(3)181-185.*

Wilson, J. 2006. Forests, carbon and climate change: A synthesis of science findings. Chapter Seven Highlights: Using Wood Products to Reduce Global Warming. Oregon Forest Resources Institute. pp. 116-129.

World Bank. 2001. Environment Strategy 2001 Document. http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/ENVIRONMENT/0,,contentMDK:20123152~menuPK:281634~pagePK:210058~piPK:210062~theSitePK:244381,00.html (Accessed 18 Sept 09.)

3 Determining stocks and flows of Structural Wood Products in Single Family Homes in the United States

3.1 Introduction

The construction industry has been the largest consumer of materials in the United States (US) for almost a century (Horvath 2004). However, detailed information on this sector's material consumption is very sparse, which is disconcerting given the sector's significant environmental and human health impacts (Ince and McKeever 1995, Franklin Associates 1998, Brunner and Rechberger 2002, Sandler 2003, Athena 2007). This lack of data is constraining sustainable development in the building sector (National Academy of Sciences 2004) and this study seeks to address some of these shortcomings. The purpose of this paper is to develop a national stocks and flows model for structural wood products in and through single family residences in the US and thereby provide important data on a key sector of the construction industry's activities. The structural wood products considered in this paper are:

- softwood lumber
- softwood plywood
- oriented strandboard (OSB)
- glue laminated timbers (glulam)
- I-joists, and
- laminated veneer lumber (LVL).

This study highlights the importance of improving the documentation of construction waste production and the removal of single family homes from the stock in order to increase the accuracy of the national stocks and flows estimates.

3.1.1 Reporting of Construction and Demolition Wastes in the Construction Industry

National estimates of construction and demolition (C&D) wastes in the US are typically extrapolated from point source samples (Ince and McKeever 1995, Franklin Associates 1998, Falk and McKeever 2004, McKeever 2004, US EPA 2009a, US EPA 2009b). Estimates of construction waste are typically expressed as the mass of waste produced per area constructed and annual material flow estimates are generated by multiplying the area constructed in a given year. Demolition waste estimates are sometimes made in the same way (Ince and McKeever 1995, Franklin Associates 1998) although others have created a profile for per person demolition waste production and determined estimates from population growth (McKeever 2004). Demolition estimates have also been calculated from averaging case study demolition waste profiles by assuming an estimated removal rate and that all homes demolished were single-family homes with the same finished floor area (US EPA 2009a).

3.1.2 Reporting of 'Wood' in the Construction Industry

Many reports have discussed the consumption of wood products in single family homes in the US. However, no publications were found that characterized and quantified the specific wood products in C&D wastes arising from single family homes or the construction industry in general. National C&D waste reports in the US have yet to provide national composition estimates (Franklin Associates 1998, US EPA 2009a), whereas national C&D wood waste reports have estimated for a single generic material category, 'wood', as individual product categories have not been specified (Ince and McKeever 1995, McKeever 1999, McKeever 2004). Reporting wood wastes at this generic level restricts their potential relevance, as specific information is needed on the products being emitted so that a broad range of users (ie. C&D waste product recovery market, academics, policy makers) can evaluate them and make effective decisions regarding their reuse or the consequence of their disposal.

As such a product specific database has never existed, it is not possible to outline the full potential of the data. However, it is clear that these data have direct application for improving the health of the economy, environment and society (Jambeck et al. 2007, EPA 2009a). This paper focuses on the development of a model to estimate stocks and flows of softwood lumber, softwood plywood, glulam, OSB, I-joists and LVL through US single family homes. The methods used to develop this model's framework are described below.

3.2 Methods

The framework of a national stocks and flows model for tracking structural wood products through single family residences in the US consisted of four high level components; the method used for tracking, the system boundaries, the variables that were used to express the model's results, and sources of data. The following sections elaborate on each of these variables.

3.2.1 Materials Tracking

This paper uses various available information sources to estimate structural wood product stocks and C&D waste flows. Structural wood product waste values were determined by applying a refined published construction waste generation rate to the initial flow of products into single family homes in the US (ie. *Gross Product Consumption*). The two main benefits of this method are that a causal link is created between what is consumed and what is emitted as waste, and it provides the ability to further specify waste characteristics based on product specific information. As recommended in literature, this paper also utilizes removal rates, calculated from US Census data, to estimate annual demolition waste flows (McKeever 1999). These distinctive methods are used to produce estimates of structural wood product stocks and flows through single family homes in the US between 1950 and 2008, with consideration of the demolition flows emitted by the stock of single family homes built between 1900 and 1950 had on demolition flows.

3.2.2 System Boundaries and Variables

The boundaries for the model included the consumption of structural wood products into the US single family residence stock and the emission of structural wood products as C&D wastes (Figure 3.1).

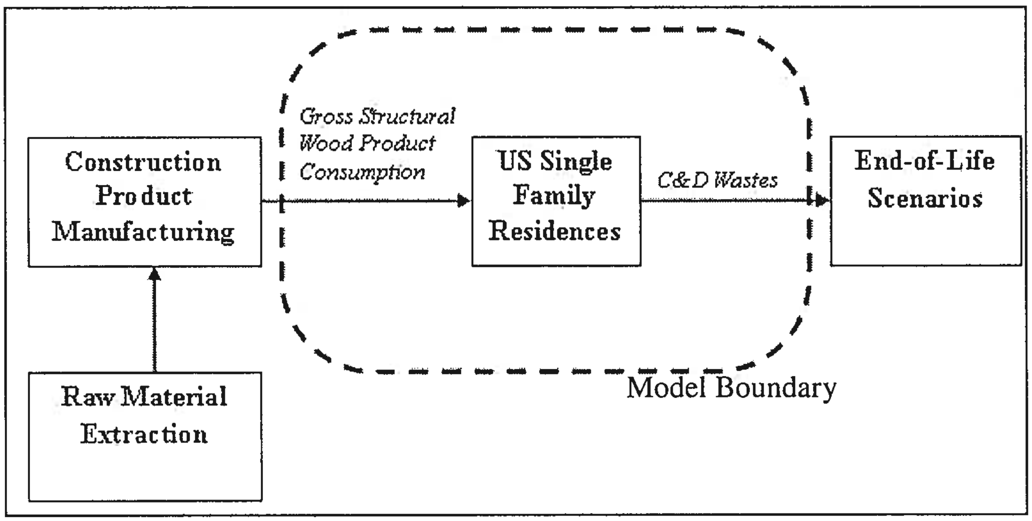

Figure 3.1 Boundary of structural wood product national stocks and flows model.

Within the model's boundary, three primary activities generate material flows over the life cycle of the building, ie. construction, renovation and demolition (Figure 3.2). The national stocks and flows model developed in this paper considers only those structural wood product that pass through US single family residences, and result from construction and demolition activities. Renovation activities and their associated stocks and flows, have thus been omitted from Figure 3.2 due to a lack of information on wood products consumed and produced from renovation activities, as well as a lack of information on residence types and the characteristics of the residence renovated in the US.

Renovation activities consume construction products, and produce both construction and demolition wastes. It is estimated that of the wood products consumed in new construction and renovation activities, 31% of the lumber (includes softwood and hardwood) and 29% of the structural panels (includes plywood and OSB) were consumed in the renovation of residential structures (includes single, multi and manufactured homes) between 1950 and 2006 (McKeever 2009). However, these estimates were not available for the respective products consumed or single family homes. Further estimates of renovation product consumption as well as waste production have were found to also report generically as residential, which encompasses single family, multi family homes and in some cases mobile or manufactured homes as well (Ince and McKeever 1995, Franklin Associates 1998, Sandler 2003, US EPA 2009a). There is a lack of information reported on the initial year of construction for residences involved in renovation activity, which the stocks and flows model also requires to develop a profile for those structural wood products displaced as demolition waste due to the consumption of new structural wood products. Without published data on these details of single family renovation activity significant assumptions would have been required to include it in the model. Thus, stocks and flows associated with renovation activity were excluded in order to mitigate the uncertainty of the figures generated by the model.

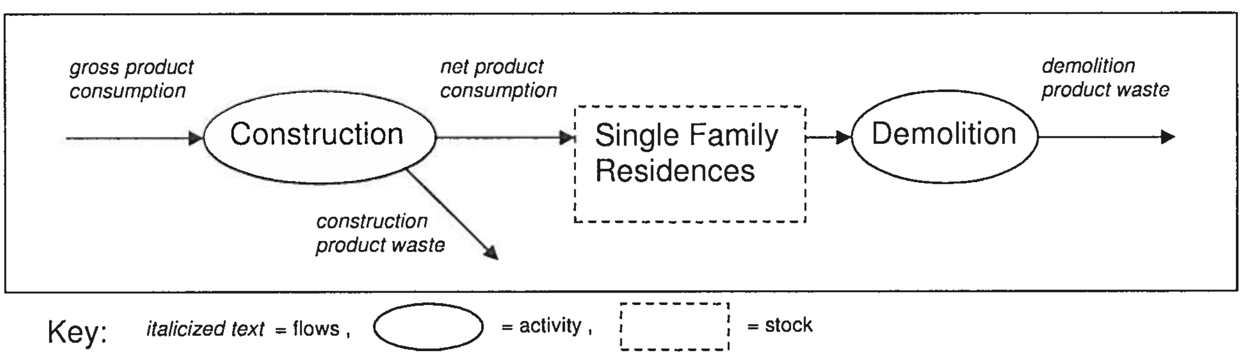

Figure 3.2 Product and waste flows included in the national stocks and flows model.

The consequences of excluding renovation wastes from the model does not affect it's construction wood waste estimates, as only waste emissions resulting from new construction are considered it its calculation. However, the exclusion of renovation wastes is expected to have a minor effect on the amount and distribution of structural wood products in the *Demolition Product Wastes* estimates. The amount *of Demolition Product Wastes* will be slightly underestimated since approximately 3% of renovation activities are associated with the additional construction of residential square area (US Census Bureau 2009). The composition of the distribution of structural wood products may vary slightly as some structural assemblies are replaced with different products through renovations. In all, it must be recognized that the majority of renovation activities do not create a change in structural wood product stocks and flows, as more than 80% of renovations are non-structural, eg. the addition or replacement of envelopes, amenities and infrastructure, such as wiring and plumbing (US Census Bureau 2009). This nature of renovation waste must also be considered when interpreting the 1996 estimate that approximately 55% of residential C&D wastes are attributed to the renovation of residential structures (Franklin Associates 1998).

The following variables were used to express the estimating figures of the stocks and flows for the structural wood products softwood lumber, softwood plywood, glulam, OSB, I-joists and LVL (Figure 3.2):

- *Gross Product Consumption*
- *Construction Product Wastes*
- *Net Product Consumption*
- *Demolition Product Wastes*
- *Net Product Stock*
- *Cumulative Net Product Stock*

These variables were determined using the following equations:

Equation 3.1 Net Product Consumption

$$\textit{Gross Product Consumption} - \textit{Construction Product Waste} = \textit{Net Product Consumption}$$

Equation 3.2 Net Product Stock

$$\textit{Net Product Consumption} - \textit{Demolition Product Waste} = \textit{Net Product Stock}$$

Equation 3.3 Cumulative Net Product Stock

$$\textit{Cumulative Net Product Consumption} = \sum_{0}^{n} (\textit{Net Product Stock}_{i})$$

where $i_0 = 1950$ and $i_n = 2008$

These variables were all quantified by weight in metric units (ie. kg and tonne).

3.2.3 Sources of Data

Although C&D waste flow results in this chapter are reported between 1950 and 2008, a study period from 1900 to 2008 was considered in the model, as approximately 10 million homes constructed prior to 1920 were still present in the 2008 single family housing stock and would have an effect on the quantity and characterization of *Demolition Product Wastes* (US Census Bureau 2009). As no data were available between 1900 and 1950, the average finished floor area for this period was assumed to be the same as that in 1950 (ie. 1061 ft^2). This is likely to be an overestimation, as an extrapolation of historical data indicates that single family housing floor areas likely increased between 1900 and 1950. This results in the model's overestimation of structural wood products stocked into those single family homes constructed pre-1950, which would in turn result in an overestimation of *Demolition Product Waste*.

The *Gross Product Consumption* of structural wood products in single family homes in the US was both sourced from literature and derived from published values when primary information was unavailable. Assumptions were required to derive figures from published values in order to complete the *Gross Product Consumption* datasets.

Complete datasets were available for softwood lumber, softwood plywood and OSB usage in single family homes in the US between 1950 and 2006 (McKeever 2009). This key publication combined published estimates with economic data and use factors in order to develop consistent wood construction product consumption estimates for the US over the period (McKeever 2009). In the model, the volume of structural wood products consumed per square meter constructed for 1900 to 1950 was assumed to be the same as that of 1950 (ie. $0.22m^3 / m^2$ constructed), softwood lumber was assumed to be used throughout, and softwood plywood was assumed to be introduced to single family construction in 1940 (APA 2009). In order to estimate consumption for 2007 and 2008, the softwood lumber, softwood plywood and OSB data were converted into consumption on a square meter of single family home constructed basis and fitted with sigmoidal curves (Carrillo and Gonzalez 2002).

Data on I-joist and LVL consumption into single family homes were available from the Cambridge Forest Products Association for 1996 to 2006 (CFPA 2009). Data from Howard 2003 were used to infer that I-joists and LVL entered the single family housing market in 1980. A sigmoidal curve was also used in this case to estimate the missing data for I-joists and LVL between 1980 and 1996, as well as 2007 and 2008.

There was a significant lack of data on the consumption of glulam by single family home construction in the US. Two Wood Product Council reports provided information on 2003 (WPC 2005) and 2006 (WPC 2009) consumption of glulam into single family homes in the US. These data were converted into consumption on a square meter of single family home constructed basis, and the average material use intensity of these two data points was assumed for all years between 1980 and 2008 (Adair personal communication 2009).

The following section describes how this information was combined with assumptions derived from literature to produce estimates for each of the variables to quantify the national stocks and flows of structural wood products through single family homes in the US.

3.3 Results and Discussion

Three variables (Construction Product Waste, Demolition Product Waste and Cumulative Net Product Stock) that were quantified by the national stocks and flows model (Figure 3.2) are presented. The following sections describe how these variables were modeled and present the results obtained on structural wood product stocks and flows.

3.3.1 Construction Product Waste

Construction Product Waste in this paper refers to those structural wood products that are wasted during the construction of new single family homes in the US. In order to develop a historical overview of the *Construction Product Waste* stream produced by single family construction activity in the US, the following assumptions were applied to all years from 1950 to 2008:

- 21.73 kg of general mixed construction waste was produced per square meter constructed (US EPA 2009a)
- 42.5% of construction waste, by weight, was wood waste (Franklin Associates 1998)
- Structural wood product consumption into was differentiated from non-structural wood products using a published distribution of their respective consumption into single family homes (McKeever 2009).

The application of these assumptions enabled annual construction waste flows to be calculated by wood product category (Figure 3.3).

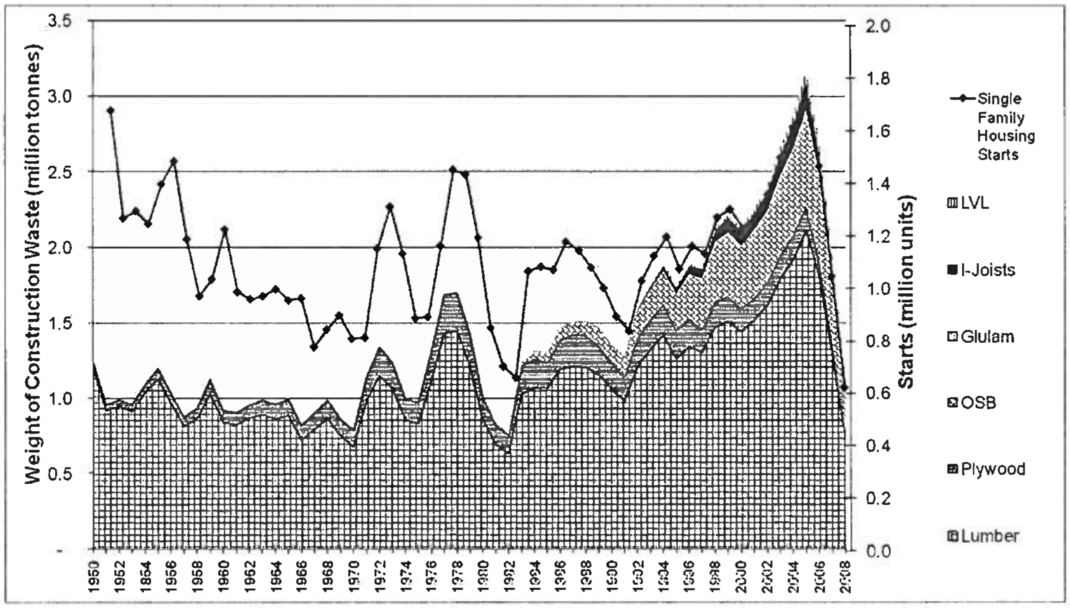

Figure 3.3 *Construction Waste* flows from single family construction activity in the US between 1950 and 2008.

(Franklin Associates 1998, Howard 2003, WPC 2005, Fuller 2007, McKeever 2009, US Census Bureau 2009, US EPA 2009a, WPC 2009)

As *Construction Product Waste* shares a direct positive correllation with single family housing starts, the 2005 peak resulted in 3.16 million tonnes of waste being generated from the construction of 1.7 million single family housing starts in that year. Figure 3.3 also illustrates the increasing mass of higher density wood products being produced per single family housing start. This can be correlated to the usage of OSB and EWPs in construction, which increase their proportion of total Construction Product Wastes up to an estimated 30.9% in 2008 (Table 3.1).

Table 3.1 Changes in proportions of structural wood products in Construction Product Waste between 1950 and 2008.

Year	Proportions of Structural Wood Products in Total Construction Waste (% of total construction waste in given year)						Total Construction Waste (million tonnes/year)
	Lumber	Plywood	OSB	Glulam	I-Joists	LVL	
1950	96.7%	3.3%	0.0%	0.0%	0.0%	0.0%	1.24
1960	91.2%	8.8%	0.0%	0.0%	0.0%	0.0%	0.92
1970	86.3%	13.7%	0.0%	0.0%	0.0%	0.0%	0.79
1980	83.4%	15.2%	0.8%	0.5%	0.0%	0.0%	1.02
1990	77.9%	13.1%	7.9%	0.5%	0.4%	0.2%	1.36
2000	67.4%	7.2%	18.9%	0.5%	4.7%	1.3%	2.14
2008	65.6%	3.5%	21.7%	0.6%	6.2%	2.4%	1.12

Published figures have typically given an overall snapshot of wood waste generation by the residential housing industry, but there are no known product specific published figures to validate the accuracy of the product level composition calculated by the model (Franklin Associates 1998, Sandler 2003). However, there are literature data with which to roughly compare the product level flows calculated by the model. Two of the publications cited in Table 3.2 have estimated the production of single family construction wood waste (Ince and McKeever 1995, McKeever 2004), and one publication provided an estimate of residential wood construction waste generation that mixes both single family and multi family (Sandler 2003). Lastly, the Franklin Associates residential construction waste was assumed to be 42.5% wood, which is an estimated percentage of single family construction waste cited in the report. In order to create comparable data to those generated by the model, the data available from Sandler 2003 and Franklin Associates 1998 were refined to roughly represent only those wood construction wastes emanating from single family construction

(US Census Bureau 2009) and only structural wood products (McKeever 2009), as seen in Table 3.2. Those non-structural wood products discounted by this method followed the consumption trends of hardwood, hardwood plywood, particleboard, medium density fiberboard (MDF), hardboard and insulation board into single family homes (McKeever 2009). In addition to this, it was also necessary to assume that multi family homes generate the same rate of wood construction waste as single family homes.

Table 3.2 Comparison of published residential structural wood construction waste and those estimated by the stocks and flows model.

Year	Single Family Structural Wood Construction Waste: Published Estimates (tons)	Single Family Structural Wood Construction Waste: Model Estimates (tons)	% Difference	Reference
1993	2,184,118	1,752,870	20%	Ince and McKeever 1995
1996	*1,979,173	1,895,260	4%	Franklin Associates 1998
1998	*2,551,230	2,139,760	16%	Sandler 2003
2002	3,019,749	2,399,600	21%	McKeever 2004

*adjusted literature data due to single family and multi family construction wood wastes being mixed

Sources of uncertainty outside those introduced as a result of refining published estimates to be comparable with the stocks and flows model, may be attributed to the methods used by publication authors to generate their estimates. As wood waste data is not collected at a national level, these publications derived estimates from existing information sources. Aside from the Franklin Associates estimates which was derived using aforementioned methods, sources referenced include; point source samples and housing starts (Ince and McKeever 1995), national levels of construction activity and population (McKeever 2004), and composition studies, sector information and expert opinion (Sandler 2003). It can be inferred that these source and the assumptions used to combine them were different as there is no standard method for extrapolating estimates of the C&D waste composition. Unfortunately, these publications do not explicitly present their methods of extrapolation, thus making it difficult to draw clear conclusions for the disparities between the published wood construction waste estimates and those estimated by the stocks and flows model.

Despite the inability to compare extrapolation methodologies, the stocks and flows model appears to estimate wood construction waste flows quite comparably with those found in literature, as it consistently estimates within approximately 20% of those estimates found in literature. In addition to this, the wood construction waste flow estimates generated by the stocks and flows model are able to be tracked back to the initial consumption of the wood products it estimates are being wasted. Those estimates found in literature do not contain this level of detail, nor is it apparent that their estimates associate waste production and product consumption. As a result of these shortcomings, it may be the case that those estimates found in literature are overestimating wood construction waste being emitted from the US construction sector.

3.3.2 Net Product Consumption

Net Product Consumption quantifies the structural wood products that are consumed in single family housing structures each year net of the quantities generated as waste during construction. This variable is calculated by determining the difference between *Gross Product Consumption* and *Construction Product Wastes* in any given year (Equation 3.1). The *Net Product Consumption* of structural wood products into US single family residences on a kilogram per square meter finished floor area constructed annually is presented in Figure 3.4. The data are given on a finished floor area basis to more clearly illustrate the changes that are occuring in the consumption of structural wood products (ie. the increasing usage of OSB and EWPs) irrespective of the increase in single family house size with time. In Figure 3.4, the values for lumber have been reduced by a factor of ten in order to more clearly see the consumption of all structural wood products.

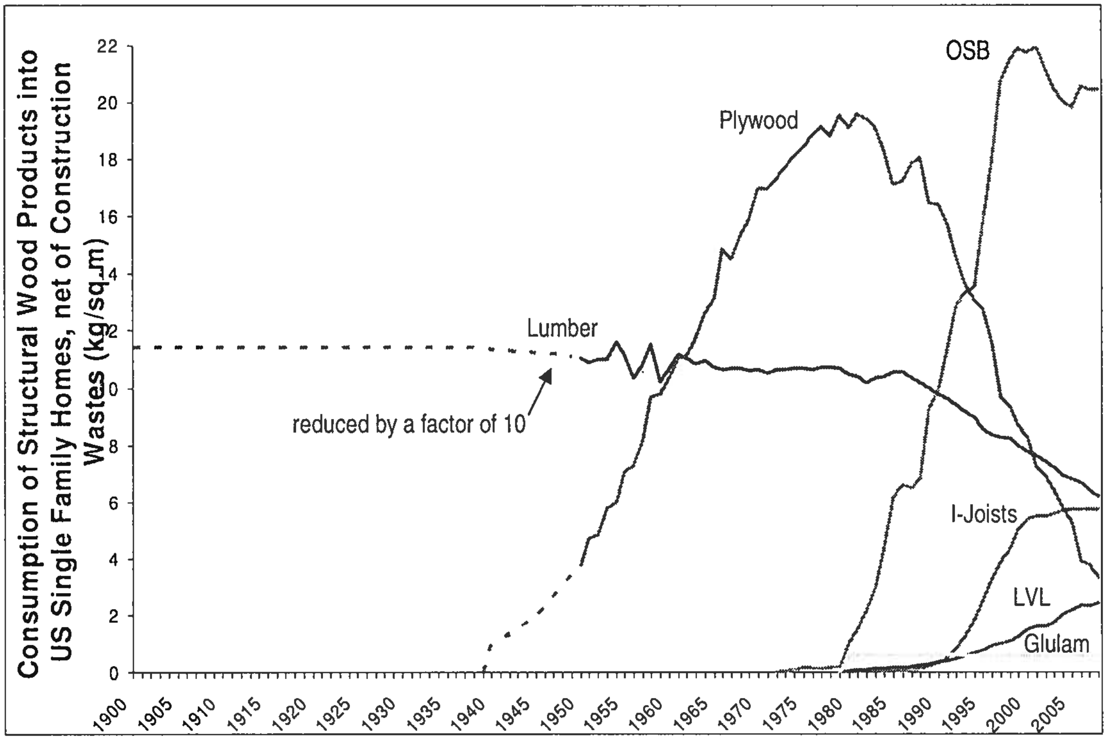

Figure 3.4 ***Net Product Consumption*** **of structural wood products, per square meter constructed, between 1900 and 2008.**

(Franklin Associates 1998, Howard 2003, WPC 2005, Fuller 2007, McKeever 2009, US Census Bureau 2009, US EPA 2009a, WPC 2009)

This comparison is very effective in determining which products are becoming substituted for and those products that have preferred characteristics for the current residential construction market environment. In the case of structural panels, it is evident that OSB has been directly substituting for plywood since the early 1980's. Softwood lumber has experienced the second largest decrease in usage intensity in US housing construction. The two main wood construction products that are substituting for softwood lumber are I-joists and LVL. Reasons for this are that builder's rate straightness and lack of defects to be the most important attributes of lumber, which were also the two attributes with the lowest satisfaction ratings between 1995 and 2001 (CINTRAFOR 2004). I-joists are mainly substituting for softwood lumber in floor framing applications, whereas LVL is mainly substituting for softwood lumber in header applications of residential construction (CINTRAFOR 2004).

Net removals from the stock must also be taken into account in order to determine the effect of material lost from the single family housing stock in the form of *Demolition Product Waste*. The national stocks and flows model estimates for *Demolition Product Waste* are explained in the following section.

3.3.3 Demolition Product Wastes

In the development of the *Demolition Product Waste* model, the historical *Net Product Consumption* of structural wood products calculated in the previous section was used. These data were combined with housing starts, average floor area and a calculated removal rate, in order to determine the amount of structural wood products emitted as waste from the demolition of homes for each year between 1900 and 2008.

In addition to inheriting the construction waste assumptions made in calculating the *Net Product Consumption* of structural wood products, the structural wood *Demolition Product Waste* model assumed that the wood products consumed in construction remained until demolition when they were completely extracted as Demolition Product Waste (Franklin Associates 1998). Further assumptions in the calculation of the removal rate of homes from the housing stock were also necessary and are explained in the following sub-section.

3.3.3.1 Removal Rate Assumptions

The *Demolition Product Waste* model was more complicated to develop than the *Construction Product Waste* model because the removal rates of single family homes from the stock needed to be determined through assumptions and calculations. Data on removal rates of residences were obtained from the bi-annual US Censuses, which track residence stocks by decade of construction. In all, data from twelve bi-annual US Censuses from 1985 to 2007 were compiled, and the average annual removal rates (Table 3.3) were used to determine an average annual increase in removals from a stock of homes constructed in a given year relative to their initial year of construction. The uncertainty contained in the US Census housing stock data is known, however historical US Census data has been considered to be the most accurate option to calculate the removal rate of homes from the stock (Wilson 2006, Belsky et al. 2007).

Table 3.3 US housing stock average annual removal rates by decade of construction between 1985 and 2007.

(US Census Bureau 2009)

Decade of Construction	Average Annual Removal Rate
<1920	-0.86%
1920	-0.56%
1930	-0.61%
1940	-0.51%
1950	-0.32%
1960	-0.36%
1970	-0.17%
1980	-0.35%
1990	-0.27%

This rate was fitted with a linear trend line, which was applied as a decay rate to the respective square footage constructed in each respective year between 1900 and 2008. As a result, the respective years of construction decay at independent rates from one another, where the rate increases each year past the construction of the square footage into the stock (Equation 3.4).

Equation 3.4 Square Footage Removal Rate for a Given Year of Construction

$$= 0.0007\left(\left(\frac{0.0078}{0.0007}\right) - \left(\frac{\left(\frac{0.0078}{0.0007}\right)}{(2008 - 1900)} \text{ x (\# of years in stock)}\right)\right) - 0.078$$

The annual flows of *Demolition Product Waste* were calculated by applying removal rates to each respective year's *Net Product Consumption* data from 1900 to 2008. In the years reported between 1950 and 2008, the *Demolition Product Waste* emitted from the removal of single family homes increased ten fold from 300,000 tonnes to approximately 3.0 million tonnes (Figure 3.5).

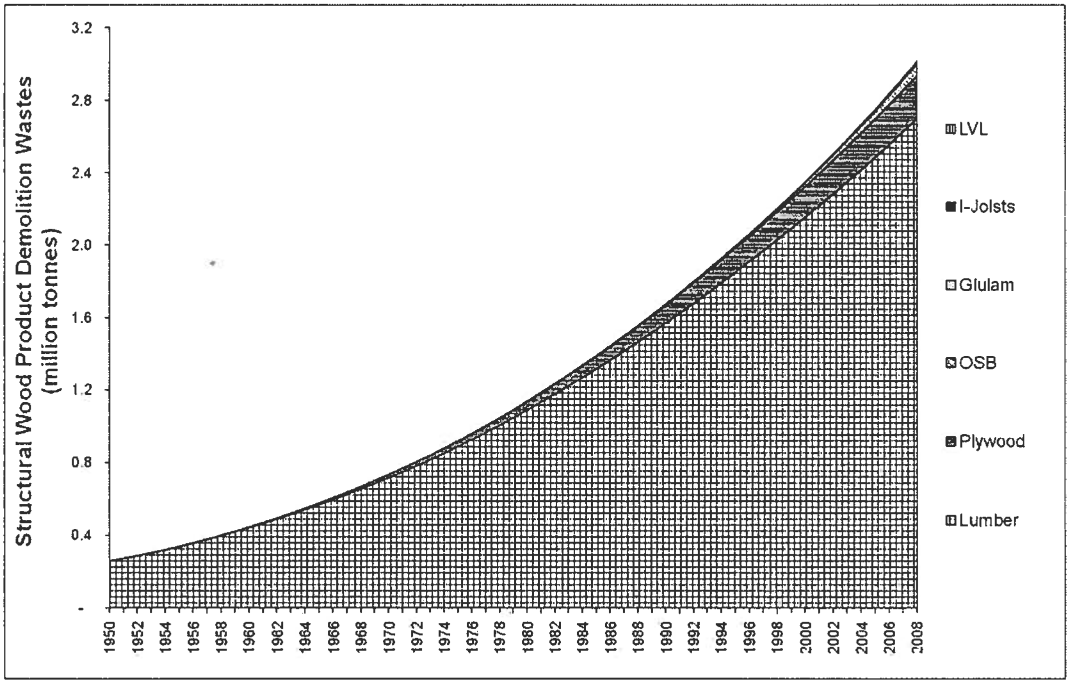

Figure 3.5 ***Demolition Product Waste*** **resulting from the removal of single family homes in the US between 1950 and 2008.**

(Franklin Associates 1998, Alexander 2000, Howard 2003, WPC 2005, Fuller 2007, McKeever 2009, US Census Bureau 2009, US EPA 2009a, WPC 2009)

Before 1950, the demolition waste stream essentially consisted of lumber. Subsequently, the proportions of plywood and, to a lesser extent, OSB and the EWPs have increasingly become important components of the demolition waste stream. This is seen as OSB and EWPs share of the *Demolition Product Waste* has increased to approximately 10.2% of the 3.0 million tonnes emitted in 2008 (Table 3.4).

Table 3.4 Contribution of various structural wood products to Demolition Product Waste flows by decade.

Year	Proportions of Structural Wood Products in Total Demolition Product Waste (% of total Demolition Product Waste in given year)						Total Demolition Product Waste (million tonnes/year)
	Lumber	Plywood	OSB	Glulam	I-Joists	LVL	
1950	99.9%	0.1%	0.0%	0.0%	0.0%	0.0%	0.26
1960	99.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.45
1970	97.5%	2.5%	0.0%	0.0%	0.0%	0.0%	0.74
1980	95.7%	4.3%	0.0%	0.0%	0.0%	0.0%	1.14
1990	93.8%	6.0%	0.1%	0.0%	0.0%	0.0%	1.67
2000	91.6%	7.4%	0.9%	0.1%	0.1%	0.0%	2.35
2008	89.5%	7.9%	2.1%	0.1%	0.3%	0.1%	3.02

There are considerable discrepancies between the information and assumptions used to extrapolate demolition wood waste in the few existing published estimates. For instance, the national demolition waste estimates for 1993 were extrapolated from a single regional study of New York (Ince and McKeever 1995). The 1996 estimate were developed from a study of three single family homes in Portland, Oregon and a single multi family unit in Maryland, and also assumed uniform areas of 1,600 ft^2 and 1,000 ft^2 respectively for each dwelling type (Franklin Associates 1998). The details to calculate the 1998 estimates are not quantitatively detailed in the publication, but does source the use of composition studies, sector information and expert opinion to generate estimates (Sandler 2003). As Franklin Associates 1998 did not extrapolate a national demolition wood waste estimate, the total residential demolition waste estimate in the report was assumed be composed of 41% wood, which is based the residential demolition composition studies cited in the report. Estimates for wood in each of these studies are also based on data largely collected in the colder northern US states, which is known to contain a higher intensity of wood usage in residential construction (McKeever and Anderson 1992, Wilson 2006). Each publication's authors acknowledge the considerable uncertainty contained in the figures they have estimated (Ince and McKeever 1995, Franklin Associates 1998, Sandler 2003). In addition to this, the 1993 and 1998 demolition disposal estimates have been discussed in literature as potentially overstating wood content by under-estimating concrete disposal due to the use of a flawed C&D landfill disposal estimation methodology (Athena 2007, Franklin Associates 1998, Sandler 2003). Any further efforts to refine published wood demolition figures to compare them with those estimated by the model would have been speculative, as the distribution of single family to multi family homes or structural to non-structural wood products is not known.

Another cause of the disparity between figures is that the removal rate of homes from the stock used by the national stocks and flows model may be too low. Although this removal rate is based on a trend calculated from US Census housing stock data, the accuracy of this stock data is questioned in other publications (Williams 2004, Belsky et al. 2007).

Although it is not possible to draw a direct comparison between published demolition wood waste values and those generated by the model, it is possible to explain the disparities seen in Table 3.5 with the following points regarding the published values, the study boundary and the methodology:

1. included multi family homes,
2. extrapolated national values from northern regional point samples that embody a larger scope of nonstructural wood products, and
3. calculated data from simplified residential demolition waste estimation models.

Table 3.5 Comparison of published residential wood construction waste and those estimated by the stocks and flows model

Year	Wood Demolition Waste		% Difference	Reference
	Published Estimates	Model Estimates		
	Residential (SF + MF)	Single Family		
	(tons)	(tons)		
1993	23,000,000	1,862,026	92%	Ince and McKeever 1995
1996	*8,000,000	2,062,361	74%	Franklin Associates 1998
1998	6,800,000	2,203,414	68%	Sandler 2003

*calculated from total residential demolition waste using an assumed 41% wood composition.

In order to complete the structural wood product national stocks and flows model, *Net Product Stocks* were calculated as the difference between *Net Product Consumption* and *Demolition Product Wastes* (Equation 3.2) and then *Cumulative Net Product Consumption* is calculated (Equation 3.3). The results of the *Cumulative Net Product Stock* calculations are presented in the following section.

3.3.4 Cumulative Net Product Stock

Net Product Stock refers to the amount of structural wood products stocked in US single family homes, net of wastes lost during construction activity and stocks removed from demolition activity. The *Net Product Stock* was calculated by taking the difference between *Net Product Consumption* and Demolition Product Wastes for each year (Equation 3.2). These values were then summed to generate an estimate of Cumulative Net Product Stock between 1900 and 2008 (Equation 3.3). The resulting estimates for the period of 1950 to 2008 are shown in Figure 3.6.

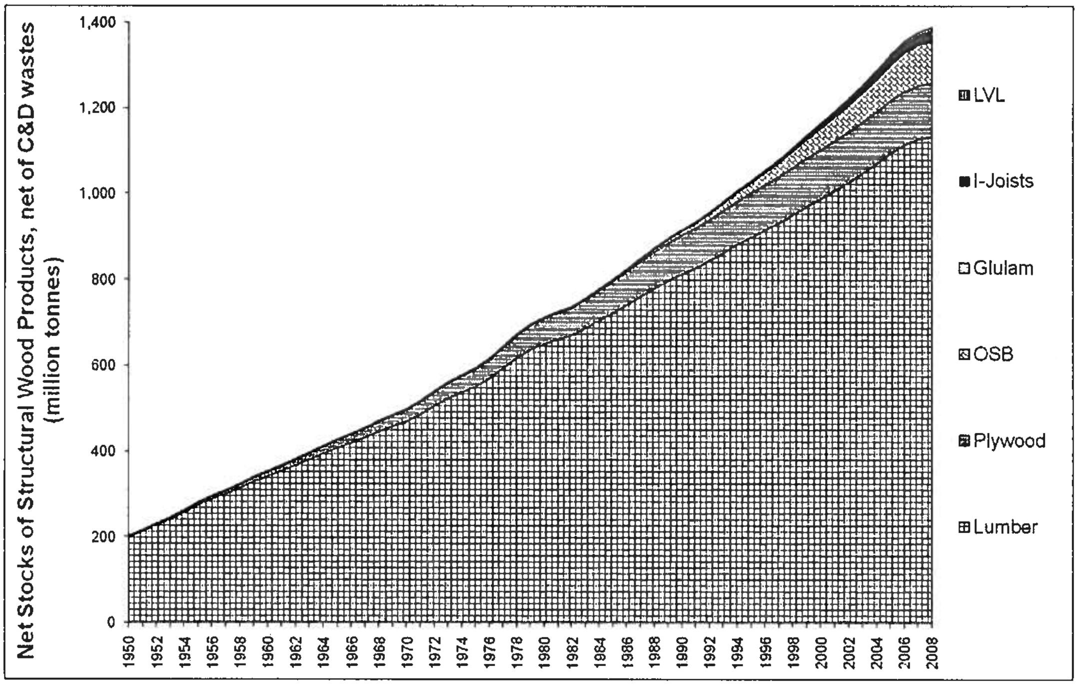

Figure 3.6 ***Cumulative Net Product Stock*** **of structural wood products accumulated into single family residences in the US between 1950 and 2008.**

(Franklin Associates 1998, Alexander 2000, Howard 2003, WPC 2005, Fuller 2007, McKeever 2009, US Census Bureau 2009, US EPA 2009a, WPC 2009)

Once again, the increasing presence of structural panels and EWPs within the stock is apparent. These changing proportions of structural wood products in US single family homes are presented in Table 3.6.

Table 3.6 Structural wood product Net Product Stock distribution changes, by weight.

Year	Proportions of Structural Wood Products in Stock (% of Total Net Product Stock)						Total Structural Wood Product Net Product Stock (million tonnes)
	Lumber	Plywood	OSB	Glulam	I-Joists	LVL	
1950	98.9%	1.1%	0.0%	0.0%	0.0%	0.0%	201.22
1960	96.6%	3.4%	0.0%	0.0%	0.0%	0.0%	353.31
1970	94.2%	5.8%	0.0%	0.0%	0.0%	0.0%	498.11
1980	91.3%	8.6%	0.0%	0.0%	0.0%	0.0%	712.13
1990	88.7%	9.9%	1.2%	0.1%	0.0%	0.0%	915.97
2000	84.7%	9.9%	4.3%	0.2%	0.6%	0.2%	1,165.67
2008	81.5%	9.1%	7.1%	0.3%	1.5%	0.5%	1,389.65

Between 1950 and 2008, approximately 1,390 million tonnes of structural wood products had accumulated in single family homes in the US. The *Net Product Stock* also demonstrated the gradual displacement of softwood lumber and plywood by OSB and EWPs, which by 2008 had increased their proportions to approximately 9.4% of all structural wood products stocked in US single family residences.

There is only one known value in the literature with which to calibrate this estimation of wood products stocked into US single family homes. The carbon stored in single family homes estimated in Wilson 2006 for 2003 was doubled in order to make it comparable with the estimate of model's estimate of structural wood products stocked in single family homes in 2003 (Wilson 2006). These figures and their scopes are quite comparable (Table 3.7) as the published figure takes into account carbon stored in structural applications only, excluding non-structural applications such as doors, moldings and millwork, cabinets, flooring and furniture from it's calculation (Wilson 2006).

Table 3.7 Comparison of published figure of carbon stored in single family residences and those estimated by the stocks and flows model.

Year	Weight of wood stocked in single family homes: Published Estimate (kg of structural wood products)	Weight of wood stocked in single family homes: Model's Estimate (kg of structural wood products)	Difference	Reference
2003	1,056,456,000,000	1,256,211,183,267	-19%	Wilson 2006

The Wilson 2006 estimate was developed to provide a general sense of the magnitude of carbon stored in wood products used in US single family homes to convey the possibility of using wood to reduce global warming. The variables used in the calculation of this figure include the average carbon storage of 4,380 kg per single family home and an estimation of 120.6 million single family homes in the US stock (Wilson 2006). Wilson 2006 rightly notes that the single family stock sourced from a 2003 US Department of Housing and Urban Development (HUD) housing inventory estimate is conservative as it had assumed a service life of 80 years despite an estimated 2003 stock of 10 million homes built prior to 1920. This comparison suggests that the model is estimating within the appropriate magnitude of structural wood products stored in single family homes in the US.

As described in the previous sections, assumptions were required in order to estimate structural wood product stocks and flows. Evaluating how these assumptions affect the results are important in understanding the limitations of the model and the results. A sensitivity analysis of the major assumptions made in the national stocks and flows model is summarized in the following section.

3.4 Sensitivity Analysis

The sensitivity analysis of the stocks and flows model assessed six major assumptions made to determine their impacts on the estimations. Assumptions included in the sensitivity analysis are described in Table 3.8.

Table 3.8 Structural wood product stocks and flows model assumptions tested in sensitivity analysis.

Assumption Reference	Description
A	Weight of construction waste produced per square meter constructed
B	Percentage of total waste produced per square meter constructed being wood waste
C	Estimates of *Gross Product Consumption* for glulam per square meter constructed
D	Estimates of *Gross Product Consumption* for I-joist per square meter constructed
E	Estimates of *Gross Product Consumption* for LVL per square meter constructed
F	Removal rate of single family homes from the stock

The value associated with each assumption was varied by +/-10%, and the impact of this change was evaluated for total *Construction Waste*, total *Demolition Product Waste* and total *Cumulative Net Product Stock*. In each case, the 'total' refers to the sum of all of the structural wood products.

3.4.1 Sensitivity Analysis Results

The sensitivity analysis revealed several important points regarding the data that most significantly affected the national stocks and flows model. It also provided useful insights into which data are the most important to collect accurately in order to increase the precision of the model. Estimates of total *Construction Waste* were vey sensitive to any changes in the amount of construction waste being produced per square meter constructed and the amount of wood present in the total construction waste being produced per square meter. Total *Demolition Product Waste* values were very sensitive to the removal rate of finished floor area from the stock (Assumption F) (Table 3.7).

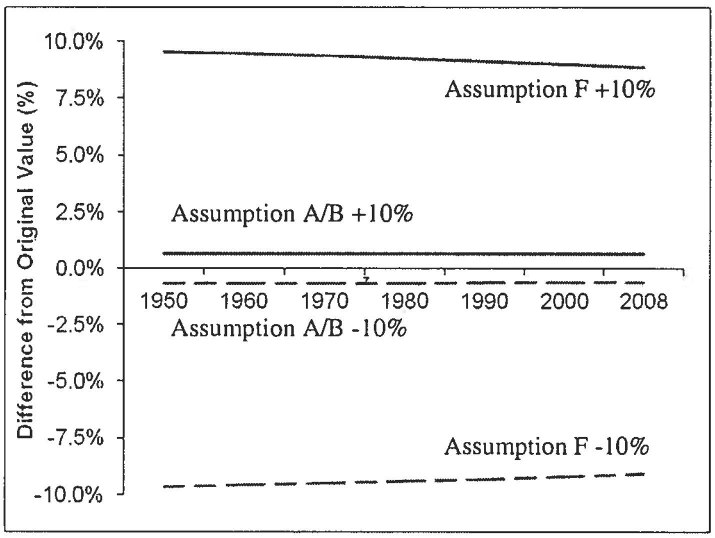

Figure 3.7 Total Demolition Product Waste Sensitivity

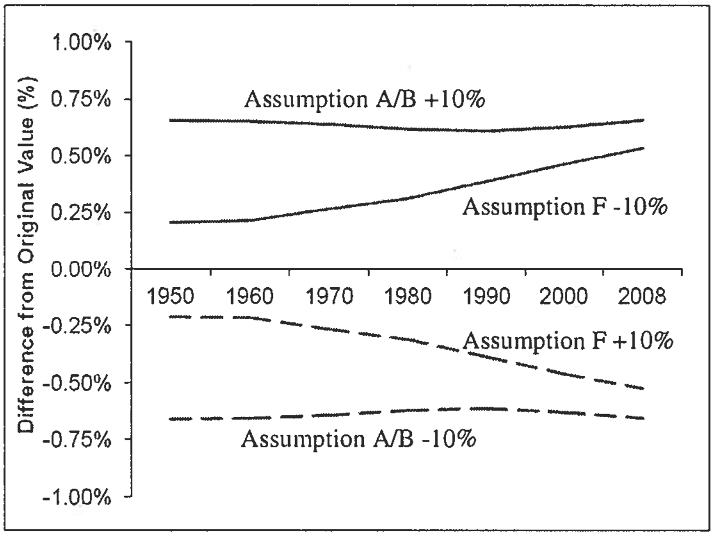

Figure 3.8 Total *Cumulative Net Product Stock* Sensitivity

Total *Cumulative Net Product Stock*, values were strongly influenced by the construction waste being produced per square meter constructed and the amount of wood present in the total construction waste being produced per square meter (assumptions A and B)(Table 3.8). Total *Cumulative Net Product Stock*'s relatively consistent sensitivity to assumptions A and B largely followed the ratio of total *Construction Waste* to total *Net Product Consumption* of structural wood products stocked into single family homes. However, the effect of varying the removal rates (assumption F) increased with time at an average rate of 0.12% per decade, and this parameter would eventually exceed the model's sensitivity to assumptions A or B. Varying glulam, I-joist and LVL consumption amounts per square meter of single family home constructed by +/- 10% did not affect any of the total *Construction Waste*, *Demolition Product Waste* and *Cumulative Net Product Stock* variables.

3.5 Conclusions

A structural wood products stocks and flows model was developed to estimate wood product specific waste flows for US single family housing between 1950 and 2008. This national model's results were expressed through variables – *Gross Product Consumption*, *Construction Product Wastes*, *Net Product Consumption*, *Demolition Product Wastes* and *Net Product Stocks* – for the structural wood products – softwood lumber, softwood plywood, OSB, glulam, I-joists and LVL.

The presence of OSB and EWPs in total *Construction Waste*, *Cumulative Net Product Stock* and *Demolition Product Waste* have respectively increased to 28.5%, 8.2% and 2.6% of wood product mass per unit area constructed, after only being introduced in the 1970s and early '80s. These results quantify the substitution occurring at the product level and their delay in being released as demolition waste. That is, the initial impacts of a changing product distribution immediately impact the *Construction Product Wastes*, then the *Cumulative Product Stock*, before finally being released as *Demolition Product Wastes.*

The main challenges of developing this national stocks and flows model were the lack of historical data on glulam, I-joist and LVL consumption in single family homes, information on finished floor area and the consumption of structural wood products between 1900 and 1950, construction waste weight and percentage of wood present in construction wastes, and records of removal rates of single family homes from the stock.

Sensitivity analyses demonstrated that the model's estimates were strongly influenced by assumptions regarding the weight of construction waste produced per square meter constructed, the proportion of total construction waste produced being associated with wood, and the removal rates of single family homes from the stock. These findings suggest that more accurate information needs to be collected on construction waste production and on the percentage of wood products within these wastes as they have the largest overall effect on results. It is also demonstrated that improved estimates of removal rates of single family homes from the stock is required, as they have a significant effect on the model's results.

The figures estimated by the national stocks and flows model quantify a causal link between the consumption, stocks and wastes of structural wood products through single family residences in the US. This type of quantified and characterized information is becoming increasingly valuable as it has the potential be integrated into holistically assessing the economic, environmental and human health impacts of consumption in order to help guide the sustainable development of wood usage in US single family residences and the construction industry as a whole.

3.6 Recommendations

The main sources of data from literature used in this national stocks and flows model on structural wood products was from housing starts, average finished floor area constructed and *Gross Product Consumption* estimates. These sources were refined through assumptions based on further published values and information. The resulting values are estimates. The accuracy of the model would be improved by obtaining more precise values based on a representative national sample of individual building level stocks and flows (ie. *Gross Product Consumption*, *Construction Product Wastes*, *Net Product Consumption*, *Demolition Product Wastes* and *Net Product Stock*). With a nationally representative sample of data collected at the individual building level, it would be possible to create a multilevel stocks and flows model, where material stock and flows data are modeled at four spatial scales; individual building, regional level, state level and national level (National Academy 2004). The availability of a multilevel stocks and flows model at these four scales would be the ideal resource to inform decision making processes, academic study and economic assessments and contribute to decision making in the sustainable use of materials by the construction industry.

Furthermore, although this paper focuses on quantifying and characterizing the variance of structural wood products within the generic classification of 'wood', there are other products that should also be the subject of further modeling and study. In addition, further generic classifications (ie. including but not limited to – drywall, metals, plastics, roofing, rubble, brick, glass, miscellaneous) which should also be the subject of future research to quantify the construction stocks and flows (Franklin Associates 1998). These data should be collected not only for single family homes, but for all building types within the construction industry. Only with the consideration of all construction products and building types will a holistic understanding of the economic, environmental, and human health impacts of the US construction industry be possible.

3.7 Works Cited

Adair, C. 2009. Personal communication 10 Aug 09. The Engineered Wood Association. Tacoma, WA.

Alexander, B.T. 2000. The U.S. homebuilding industry: A half-century of building the American dream. John T. Dunlop Lecture. Harvard University.

APA. 2009. Softwood plywood industry celebrates 100th anniversary. APA - The Engineered Wood Association. http://www.apawood.org/level_b.cfm?content=srv_med_new_bkgd_ply100 (Accessed 20 July 09.)

Athena. 2007. Construction and demolition waste in the US and Canada, September 2007. Athena Institute International, Merrickville, ON. pp 28.

Belsky, E., R. Drew and D. McCue. 2007. Projecting the underlying demand for new housing units: Inferences from the past, assumption about the future. W07-7. Joint Center for Housing Studies. Harvard University. 50 pp.

Brunner, P. and H. Rechberger. 2002. Anthropogenic Metabolism and Environmental Legacies: Causes and Consequences of Global Environmental Change (Vol. 3). John Wiley and Sons, Ltd, Chichester, England. pp. 54-72.

Carrillo, M. and J.M. Gonzalez. 2002. A new approach to modelling sigmoidal curves. Technological Forecasting and Social Change. 69(3):233-241.

CFPA. 2009. North American EWP : Significant market growth unlikely before 2009. Cambridge Forest Products Associates. http://www.cambridgeforestproducts.com/images/presentations/BF-NAConf07CFPA.pdf (Accessed 12 July 09.)

CINTRAFOR. 2004. Material substitution trends in residential construction 1995, 1998 and 2001, April 2004. Center for International Trade in Forest Products. Working Paper 93: Garth, J., Easton, I., and Edelson, J. pp. 101.

Falk, R.H. and D.B. McKeever. 2004. Recovering wood for reuse and recycling: A United States perspective. In, Management of Recovered Wood Recycling, Bioenergy and Other Options. University Studio Press, Athens, Greece. pp. 29-40.

Franklin Associates. 1998. Characterization of building-related construction and demolition debris in the United States, June 1998. US Environmental Protection Agency. Municipal and Industrial Solid Waste Division. Office of Solid Waste. EPA530-R-98-010. Washington, DC.

Fuller, B. 2007. North American EWP: Significant market growth unlikely before 2009. Cambridge Forest Products Associates. http://www.cambridgeforestproducts.com/images/presentations/BF-NAConf07CFPA.pdf (Accessed 20 Aug 09.)

Horvath, A. 2004. Construction materials and the environment. The Annual Review of Environment and Resources. 29:181-204.

Howard, J. 2003. US timber production, trade, consumption, and price statistics 1965-2002. US Department of Agriculture, Forest Service, Forest Products Laboratory, Washington, DC. 90 pp.

Ince, P. J. and D.B. McKeever. 1995. Recovery of paper and wood for recycling: Actual and potential. General Technical Report FPL-GTR-88. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 13 pp.

Jambeck, J., K. Weitz, H. Solo-Garbriele, T. Townsend and S. Thorneloe. 2007. CCA-treated wood disposed in landfills and life-cycle trade-offs with waste-to-energy and MSW landfill disposal. Waste Management. 27(8):S21-8.

McKeever, D.B. 1999. Changes in the US Solid Waste Wood Resource, 1990 to 1998. US Department of Agriculture, Forest Products Laboratory, Madison, WI. 14 pp.

McKeever, D.B. 2004. Inventories of woody residue and solid wood waste in the United States, 2002. US Department of Agriculture, Forest Products Laboratory, Madison, WI. 16 pp.

McKeever, D.B. 2009. Estimated annual timber products consumption in major end uses in the United States, 1950-2006. General Technical Report FPL-GTR-181. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 47 pp.

McKeever, D.B. and R.G. Anderson. 1992. Timber products used to build US single-family houses in 1988. Forest Products Journal. 42(4):11-18.

National Academy. 2004. Materials Count: The Case for Material Flows Analysis. National Academy of Sciences. National Academies Press, Washington DC. 124 pp.

Sandler, K. 2003. Survey Statistics: Analyzing what's recyclable in C&D debris. BioCycle. 44(11):51-54.

US Census Bureau. 2009. American Housing Survey. http://www.census.gov/hhes/www/housing/ahs/nationaldata.html (Accessed 15 July 09.)

US EPA. 2009a. Estimating 2003 building-related construction and demolition material amounts. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-002. Washington, DC. 60 pp.

US EPA. 2009b. 2008 Sector performance report. United States Environmental Protection Agency. Sector Strategies Division. Office of Cross Media Programs. EPA 100-R-08-002. Washington, DC. 138 pp.

Williams, B. 2004. Current housing reports: These old houses: 2001. US Census Bureau. US Department of Housing and Urban Development, US Department of Commerce. H121/04-1. Washington, DC. 49 pp.

Wilson, J. 2006. Forests, carbon and climate change: A synthesis of science findings. Chapter Seven Highlights: Using Wood Products to Reduce Global Warming. Oregon Forest Resources Institute. pp. 116-129.

WPC. 2005. Wood products used in new residential construction in the US and Canada 1995, 1998 and 2003. Wood Products Council. Tacoma, WA. 28 pp.

WPC. 2009. 2006 Wood used in new residential construction in the US and Canada, with comparison to 1995, 1998 and 2003. Wood Products Council. Tacoma, WA. 169 pp.

4 Concluding Chapter

4.1 Research Overview

C&D wastes emitted from the US construction sector represent one of the largest solid waste flows in the US. As the majority of these wastes are landfilled, the US construction sector is also significantly underutilizing resources which necessitate further resource extractions from an overburdened environment. It is apparent that there is growing public concern regarding this issues as market demand is significantly increasing for C&D waste product recovery firms involved in handling and processing C&D wastes diverted from landfills (US EPA 2009a). However, as there is very little collection and reporting of information to support estimates of national disposal or diversion rates of C&D waste, there is little known of the effectiveness of diversion efforts in this regard (Horvath 2004). Furthermore, this lack of C&D waste flow information was shown to be a key in supporting the effective positioning of the C&D waste product recovery market, as this information supports the exploration of wants and uses of potential C&D wastes, development of competitive business strategies and planning of operations. Thus, as none of these applications are possible without C&D waste flow information, this thesis contended that the current data collection and quality of reported information on the US construction sector's C&D waste flows are major barriers to the optimal development of the C&D waste product recovery market.

This contention was addressed by raising awareness of C&D waste flow information's role in the optimal development of C&D waste product recovery markets as well as the purpose of this thesis, which was to address the collection and quality of information inherent in currently available C&D waste estimates for the US construction sector. To achieve this purpose and awareness, two manuscript chapters that addressed the methods and data quality issues inherent in currently available C&D waste estimates were presented.

The second chapter in this thesis entitled *Developing the Reuse and Recycling Market: Improving Empirical Data Collection Methods to Increase the Applicability of US C&D Waste Estimates* addressed the high levels of uncertainty and significant methodological shortfalls of the current US EPA national C&D waste estimate for 1996 as reported by Franklin Associates 1998. In this report, high levels of uncertainty were found to exist due to the lack of standardized collection methods and the small sample of buildings from which data were collected. Furthermore, the 1996 C&D waste flow estimates contain a low data resolution and temporal limitations as well as restricted geographical reach, which make it impractical to identify C&D waste product waste types, sources and trends as a result. To address these uncertainties and shortfalls, this chapter developed a framework to improve the collection methods used and the resolution of the empirical data collected on C&D waste flows. These improvements included; measurement of data at the construction site, use of standardized reporting procedures, differentiation of renovation construction and renovation demolition wastes, accounting of construction materials stocked in buildings, characterization of materials at a product level and implementation of regulatory mechanisms. The conceptual framework for addressing the uncertainties and shortfalls would significantly contribute to increasing the quality of reported information of C&D wastes and the optimal development of the C&D waste product recovery market.

The third chapter related to the second chapter through utilizing two of the second chapters suggested improvements in providing an example of C&D waste flow estimates which accounted for construction materials stocked into buildings and characterized construction materials at the product level.

The third chapter in this thesis entitled *Determining Stocks and Flows of Structural Wood Products in Single Family Homes in the United Stated* developed a national stocks and flows model for structural wood products in and through single family residences in the US between 1950 and 2008. The decision to focus on single family homes and structural wood product consumption in the US construction sector was due to these areas having the largest the most complete information available as well as published estimates to compare model estimates against. In this analysis, structural wood products contained within the generic classification of 'wood' within C&D wastes were identified. This resulted in a product specific estimate for C&D waste flows of softwood lumber, softwood plywood, OSB, glulam, I-joists and LVL. As a result of this product specific analysis, it was discovered that since being introduced into single family home construction in the 1970s-early 80s, the proportions of engineered wood products had increased to 28.5%, 8.2% and 2.6% in each of the *Construction Waste*, *Cumulative Net Product Stock* and *Demolition Product Waste* categories respectively. Furthermore, the overall analysis revealed a peak emission of 3.16 million tonnes of *Construction Product Wastes* in 2005, and *Demolition Product Wastes* and *Cumulative Net Product Stock* increasing to 3.02 and 1,389.64 million tonnes respectively by 2008. Overall, this analysis provided important data on a key sector of the construction industry's activities and demonstrated how the waste characteristics as well as their flows change with time. In the cases of *Construction Product Wastes* and *Cumulative Net Product Stock*, estimates were within 20% of comparable published figures (Ince and McKeever 1995, Franklin Associates 1998, Sandler 2003, McKeever 2004, Wilson 2006). This stocks and flows model used the most complete information available on single family homes in the US to develop an example of the type of quantified information on structural wood C&D waste products that would be support the optimal development of the C&D waste product recovery market more appropriately than currently available information. The methodology developed may also be applied to other C&D waste materials, provided sufficient data were available.

4.2 Strengths and Weaknesses of Research

A number of strengths and weaknesses exist within the materials presented in the manuscript chapters. The following section discusses the strengths and weaknesses of the two manuscript chapters.

4.2.1 Second Chapter Strengths and Weaknesses

The strengths and weaknesses of the second chapter were primarily related to the theoretical development of the recommended improved collection methods.

Strengths of this theoretical development were the possibility to explore solutions to the many existing flaws in current national C&D waste flow reports and outline a best case scenario for improving upon the uncertainties and shortcomings. This approach also permitted the presentation of a complete framework of recommended data improvement that that addressed each of the identified uncertainties and shortcomings in current national C&D publications. This framework provided a basis for further discussion of how such a collection method may operate.

The weaknesses of this theoretical development included the high level recommendations that were not fully detailed or tested at the working level where they would need to be implemented. To improve upon this weakness, the recommendations need to be developed in conjunction with research into practical working level solutions and organizations that would best serve the suggested collection framework. This will also be a key in gaining the cooperation of those organizations directly involved in construction activities through careful consideration of their operations and constraints (ie. time and budget). Further research should also focus on drawing upon information from different scales of current C&D waste estimation frameworks, such as at the individual building, regional and state levels.

The strengths and weaknesses of the theoretical development provided both a complete set of recommendations and a basis for research to improve upon current collection methods.

4.2.2 Third Chapter Strengths and Weaknesses

As the third chapter developed a stocks and flows model that estimated C&D waste flows with a higher resolution than currently available estimates, its strengths and weaknesses were primarily related to the quality of these estimates.

The main strength of the third chapter was the achievement of an accurate multi-year, product level estimation of stock and C&D waste flow information based on a causal link to the consumption of construction products. By developing this causal relationship for the stocks and flows of structural wood products in single family homes, a holistic view connecting the consumption and production of waste was possible. This is the only known C&D waste flow model that provides research on how product consumption affects waste production. A further strength of this paper is that it defines the distinct contributions of structural wood products to *Construction Product Wastes* and *Cumulative Net Product Stock* within 20% of comparable published figures (Ince and McKeever 1995, Franklin Associates 1998, Sandler 2003, McKeever 2004, Wilson 2006). Lastly, the third chapter's multi-year estimates provides further insight into the trends of structural wood C&D waste flows and their stocks into single family homes. These strengths are emphasized when considering that current national estimates do not establish a causal link or report the contribution of respective wood products in their estimates and are limited to single year estimations.

The weaknesses of the third chapter relate to the quality of its estimation being derived from available publications. For instance, available publications limited the model from including further wood products outside structural wood products or buildings types other than single family. The model was also limited from including estimates of the impacts of single family renovations on stocks and C&D waste flows. Being limited to available publications also meant that some assumptions were required in order to complete the stocks and flows model. The most significant assumptions identified by the sensitivity analysis related to the amount of structural wood product construction waste produced per square meter constructed and the removal rate of single family homes from the stock.

These weaknesses in the quality of the estimated stock and C&D waste flows of structural wood products indicate that further contributions are necessary in order to improve and broaden the estimating capabilities of models in the future.

Though limited by the availability of information current wood product stock and C&D waste flow as well as building type publications, the third chapter's multi-year, product level estimation of stocks and C&D waste flows based on a causal link to the consumption of construction products provided a strong example to be considered in subsequent models estimating stocks and flows of construction products.

4.3 Overall Significance and Contribution

Through the two manuscript chapters, this thesis highlighted the importance of the role that good quality data collection and information reporting play in supporting efforts to increase the diversion of C&D wastes from landfills. As identified in the introductory chapter, the lack of C&D waste product information is inhibiting the development of a rationally guided and competitive C&D waste product recovery market, as firms require this information to plan operations and develop value-adding strategies with it. Thus, low quality information presents a significant barrier to the development of a successful market, which in turn will divert less C&D waste from the landfill. Whereas, a C&D waste product recovery market with access to high quality information should be more successful, thus diverting higher amounts of C&D wastes from the landfill. These concepts of the importance of high quality data collection and information reporting are not recognized in current national C&D waste estimates. For instance, the Franklin Associates 1998 study suggests that the main barriers to increased diversion rates are the cost of collecting, sorting and processing low value recyclable materials in relation to the cost of virgin materials, and the low cost of landfilling C&D debris. Previous studies have not explicitly mentioned the important role of C&D waste flow information as a pivotal tool in exploring, assessing and developing C&D waste product recovery market opportunities and competitive business strategies. In this sense, a major contribution of this thesis is the suggestion that further consideration must be given to the role that a lack of high quality information on C&D waste flows plays in strengthening those barriers suggested by Franklin Associates 1998. There is a clear need to improve the quality of C&D waste information collected and reported in order to strategically and rationally move forward with increasing the diversion of C&D wastes from landfill. This thesis contributes to this need through the frameworks and model it has developed.

4.4 Future Research Directions

As there is a lack high quality empirical data on C&D waste flows emitted from activities in the US construction sector, future research in this field should focus on developing applied case studies that produce scalable results. These applied case studies should see researchers, construction and C&D waste product recovery firms and governments collaborating in order to ensure the development of rigorous and practical studies. They should also investigate the economic and environmental implications of improved C&D data collection frameworks and higher quality reporting. These case studies would be ideal testing grounds for the recommendations made in the chapters of this thesis, such as including the consumption of all construction products and their emission as C&D wastes at various scales (eg. individual building, region, state, national). Such case studies would provide the ideal forum for refining collection and reporting requirements and testing the practicality of the proposed framework. Through such case studies frameworks and concepts can be refined through rigorous and practical testing in order to develop the body of knowledge necessary to operationalize them and support further study of the economic and environmental implications of landfilling C&D wastes. This is an ideal foundation to inform public and political groups in order increase their support and put additional resources behind developing C&D waste product recovery market infrastructures and the increased diversion of C&D wastes from landfilling.

4.5 Works Cited

Brunner, P. and H. Rechberger. 2002. Anthropogenic Metabolism and Environmental Legacies: Causes and Consequences of Global Environmental Change (Vol. 3). John Wiley and Sons, Ltd. Chichester, England. pp 54-72.

Cochrane, K., Dubey, B., Henry, S. and T. Townsend. 2007. Government policies for increasing the recycling of construction and demolition debris. Clay County Solid Waste Division. Florida Department of Environmental Protection. pp 18.

Franklin Associates. 1998. Characterization of building-related construction and demolition debris in the United States, June 1998. US Environmental Protection Agency. Municipal and Industrial Solid Waste Division. Office of Solid Waste. EPA530-R-98-010. Washington, DC.

Horvath, A. 2004. Construction materials and the environment. The Annual Review of Environment and Resources. 29:181-204.

Ince, P. J. and D.B. McKeever. 1995. Recovery of paper and wood for recycling: Actual and potential. General Technical Report FPL-GTR-88. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 13 pp.

McKeever, D.B. 2004. Inventories of woody residue and solid wood waste in the United States, 2002. US Department of Agriculture, Forest Products Laboratory, Madison, WI. 16 pp.

McKeever, D.B. 2009. Estimated annual timber products consumption in major end uses in the United States, 1950-2006. General Technical Report FPL-GTR-181. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 47 pp.

Sandler, K. (2003). Survey statistics: Analyzing what's recyclable in C&D debris. BioCycle. 44(11):51-54.

US EPA. 2009a. Estimating 2003 building-related construction and demolition material amounts. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-002. Washington, DC. 60 pp.

US EPA. 2009b. "Green Servicizing" for a more sustainable US economy: Key concepts, tools and analyses to inform policy engagement. US Environmental Protection Agency. Office of Resource Conservation and Recovery. EPA530-R-09-006. Washington, DC. pp 129.

Wilson, J. 2006. Forests, carbon and climate change: A synthesis of science findings. Chapter Seven Highlights: Using Wood Products to Reduce Global Warming. Oregon Forest Resources Institute. pp. 116-129.