Determining Stocks and Flows of Structural Wood Products in Single Family Homes in the United States between 1950 and 2010

Robert A. Sianchuk
Emmanuel K. Ackom
Paul N. McFarlane

Abstract

The stocks and flows of six major structural wood products (SWPs)—lumber, plywood, oriented strand board [OSB], glue laminated timber, I-joists, and laminated veneer lumber (LVL)—in US single family homes were modeled from 1950 to 2010. The consumption of these products in US single family homes and their emissions as construction and demolition wastes were estimated. The net consumption of SWPs decreased from 119 kg/m^2 constructed in 1986 to 82 kg/m^2 in 2010. Softwood lumber was consistently the predominant SWP, but its usage intensity decreased from 95 kg/m^2 in 1986 to 52 kg/m^2 in 2010. Since the 1980s, modern SWPs, such as I-joists, LVL, and OSB, have replaced lumber and plywood products. The needs of the US single family housing industry have been met by a smaller mass of SWPs per unit area constructed.

The mass of SWP present in construction wastes was influenced strongly by building cycles. Production of construction waste peaked in 2005, when 3.31 million tonnes of SWPs were produced by 1.72 million single family housing starts. It diminished to 0.874 million tonnes of SWPs as the housing starts fell to 445,000 in 2009. In contrast, the mass of demolition wastes produced was affected substantially by the number of houses in the stock and their half-lives. Approximately 4.5 million tonnes of SWP demolition waste were produced in 2010, and in the same year, the stock of SWPs in US single family homes reached 1,220 million tonnes.

The construction industry has been the largest consumer of materials in the United States for almost a century (Horvath 2004). However, relatively little information is available on this sector's material consumption, which is disconcerting given its 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 has constrained the sustainable development of the building sector (National Academy of Sciences 2004). This study addresses some of these shortcomings by developing a model that quantifies the national stocks and flows of structural wood products in single family residences in the United States. The structural wood products considered in this model are softwood lumber, softwood plywood, oriented strand board (OSB), glue laminated timbers (glulam), I-joists, and laminated veneer lumber (LVL).

This investigation provides new information on a key sector within the construction industry and highlights the importance of improving the documentation and characterization of construction and demolition wastes.

National estimates of construction and demolition (C&D) wastes in the United States have been typically extrapolated from point source samples (Ince and McKeever 1995; Franklin Associates 1998; Falk and McKeever 2004; McKeever 2004; US Environmental Protection Agency [US EPA] 2009a, 2009b). Estimates of national construction

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The authors are, respectively, MASc Candidate, Dept. of Wood Sci., Faculty of Forestry, Univ. of British Columbia, Vancouver, British Columbia, Canada (rob.sianchuk@gmail.com [corresponding author]); Senior Scientist and Programme Manager, UNEP Risoe Centre, DTU Management Engineering, Technical Univ. of Denmark, Roskilde (emac@win.dtu.dk); and Professor, Dept. of Wood Sci., Faculty of Forestry, Univ. of British Columbia, Vancouver, British Columbia, Canada (Paul.McFarlane@ubc.ca). Robert Sianchuk is currently a Partner of Coldstream Consulting, Vancouver, British Columbia, Canada (rob.sianchuk@coldstreamconsulting.com). This paper was received for publication in February 2012. Article no. 12-00012.

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waste are usually expressed as the mass of waste produced per area constructed, and annual material flow estimates are generated by multiplying this number by the area constructed in a given year. Some demolition waste estimates have been made in the same way (Ince and McKeever 1995, Franklin Associates 1998), although other studies have calculated demolition waste production on a per capita basis and determined estimates from population growth (McKeever 2004). Demolition estimates have also been determined by 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).

Several reports have discussed the consumption of wood products by single family homes in the United States (Howard 2003; Wood Products Council [WPC] 2005, 2009; Wilson 2006; Cambridge Forest Products Associates [CFPA] 2009; McKeever 2009). 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. C&D waste reports in the United States have yet to provide national composition estimates (Franklin Associates 1998, US EPA 2009a), because national C&D wood waste reports have only estimated the single generic material category, ''wood,'' with individual product categories not being specified (Ince and McKeever 1995; McKeever 1999, 2004). Reporting wood wastes at this generic level restricts their potential relevance because specific information is needed on the individual products being emitted so that users can evaluate them and make effective decisions regarding their reuse or disposal.

Because such a product-specific database has never existed, it is not possible to outline the full potential of the data. However, such data are likely to be useful for improving the health of the economy, environment, and society (Jambeck et al. 2007, US EPA 2009a). In order to provide a foundation for a product-specific database, this article focuses on the development of a model to estimate stocks and flows of the major structural wood products through US single family homes.

Methods

The methodology used to develop the single family housing stocks and flows model of structural wood products in US single family residences consisted of three components: definition of the system's boundaries, the model's structure, and sources of data. The following sections elaborate on the first two of these components. Details on the third element are presented in the Appendix.

System boundaries

The model quantified the consumption of six structural wood products into the stock of US single family homes and the emission of these products as C&D wastes. The wood products quantified were lumber, plywood, OSB, glulam, LVL, and I-joists. The system boundaries of this model are presented in Figure 1. Any material flows outside the dotted box were not included in the model. Within this boundary, three activities generate material flows over the life cycle of the building: construction, renovation, and demolition. The model presented in this article only considers material flows arising from construction and demolition activities (Fig. 1). Owing to a lack of information on the quantities and types of wood products consumed and produced by renovation, stocks and flows associated with renovation activities were omitted. The impact of this decision on model outputs is considered in the discussion section of this article.

Model structure

The following parameters were used to determine the stocks and flows of structural wood products (Fig. 1): gross product consumption, construction product waste, net product consumption, demolition product waste, net product stock, and cumulative net product stock.

Publicly available information was used to estimate the six parameters listed above on an annual basis. Product stock and waste quantities were determined by applying a construction waste generation rate to the initial flow of products into single family homes. Two benefits of this method are that a causal link is created between material consumption and waste emission, and detailed waste characteristics may be determined based on product-specific inputs. These parameters were determined using the following equations, which were used to develop an Excel-based model where all variables were quantified by weight in metric units.

Gross product consumption.—Gross product consumption estimated the total mass of structural wood products consumed annually by single family homes in the United States. The masses of individual wood products were estimated on a kilograms per square meter constructed basis using published sources (see the ''Net product consumption'' section). These values were then multiplied by the floor area of single family homes constructed annually.

$$\text{Gross product consumption} = \text{GSWP} \times \text{AFAC} \qquad (1)$$

where

GSWP = annual gross structural wood product (SWP) input by individual product category (kg of SWP consumed/m^2 of single family home constructed annually) and

AFAC = annual floor area constructed (m^2 of single family homes constructed/y).

Construction product waste.—Construction product waste estimated the structural wood products that are wasted during the construction of new single family homes in the United States.

$$\text{Construction product waste} = (\text{CWGR} \times \text{RSWP} \times \text{ISWPR} \times \text{AFAC}) \qquad (2)$$

where

CWGR = construction waste generation rate (kg of generic wood product waste/m^2 of single family home constructed) = 9.22 kg/m^2 (US EPA 2009a, Franklin Associates 1998),

RSWP = ratio of structural wood products consumed by single family home construction (m^3 of SWP consumption/m^3 of structural and nonstructural wood products consumption), and

ISWPR = individual SWP consumption ratio for single family home construction (kg of individual SWP consumed [e.g., lumber, OSB, etc.]/kg of total SWPs consumed).

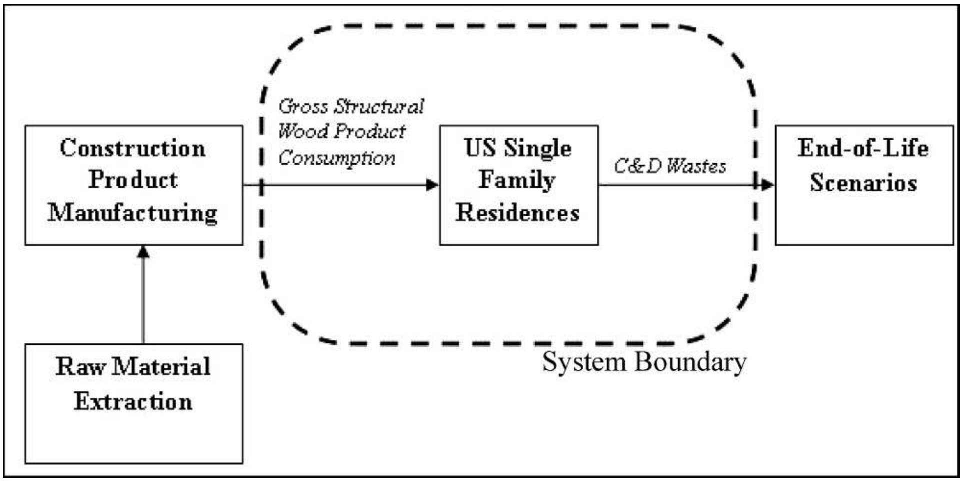

Figure 1.—System boundary for assessing the stocks and flows of structural wood products in single family residences in the United States.

Net product consumption.—Net product consumption quantified the net mass of structural wood products consumed annually into single family homes by reducing the gross mass consumed by the amount lost as waste during construction:

$$\text{Net product consumption} = \text{Gross product consumption} - \text{Construction product waste} \quad (3)$$

Demolition product waste.—Demolition product waste determined the annual mass of structural wood products produced by the demolition of single family homes (Eq. 4). The cumulative net stock of individual wood products was calculated by summing the annual net product consumption values determined using Equation 3. This value was then divided by the cumulative area of single family homes constructed to determine the mass per unit area of individual structural wood products. An Excel spreadsheet was constructed to determine the annual area of single family homes removed by demolition using half-life data from McFarlane et al. (submitted for publication). Demolition product waste was then determined by multiplying the mass per unit area value by the area removed annually as shown in Equation 4:

$$\text{Demolition product waste} = (\text{CNPC}/\text{CFAC}) \times \text{AHDA} \quad (4)$$

where

CNPC = cumulative weight of individual structural wood products in single family homes (kg),

CFAC = cumulative floor area of single family homes constructed (m^2), and

AHDA = area of houses demolished annually (m^2/y).

Net product stock.—Each year houses are added to the stock by construction and removed by demolition (Fig. 2). The annual net product stock was calculated by subtracting the annual demolition product waste from the annual net product consumption using Equation 5.

$$\text{Net product stock} = \text{Net product consumption} - \text{Demolition product waste} \quad (5)$$

Cumulative net product stock.—By summing the annual net product stock values, the cumulative net product stock of structural wood products in US single family houses may be determined.

$$\text{Cumulative net product stock} = \sum_{0}^{n} (\text{Net product stock}_i) \quad (6)$$

where

$i_0 = 1900$ and

$i_n = 2010$.

Although this article reports on product stocks and waste flows from 1950 to 2010, the model used data from 1900 to 2010 in order to develop a representative stock of structural wood products prior to 1950. For example, the US Census reported that just over 9 million homes constructed prior to

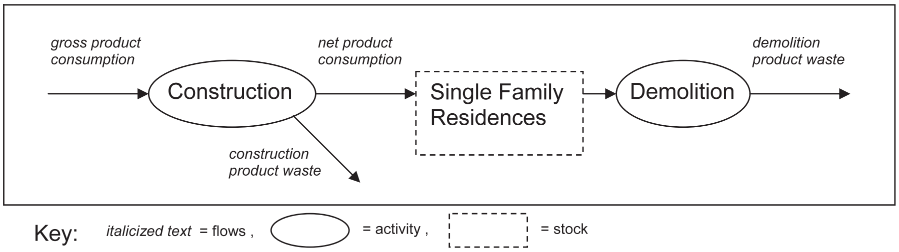

Figure 2.—Structural wood product consumption and waste flows included in the stocks and flows model.

1920 remained in the housing stock in 2009. Thus, it was important for the model to consider sufficient pre-1950 data to increase the accuracy of estimates. The assumptions associated with this modeling are presented in the Appendix.

Results and Discussion

The national stocks and flows model was used to calculate annual construction product waste flows, demolition product waste flows, and cumulative net product stocks for the period 1950 to 2010. These results are presented and discussed in the following sections.

Construction product waste

The annual structural wood product waste flows from constructing single family homes in the United States are presented in Figure 3. This graph reveals three major trends. First, the annual total waste flow is positively correlated (correlation coefficient = 0.888) with single family housing starts.

The total amount of construction waste produced annually is influenced strongly by the building cycles associated with the changes in economic activity. Production of construction waste peaked in 2005 when 3.31 million tonnes were produced by 1.72 million single family housing starts. This diminished to 0.82 million tonne as the housing starts fell to 445,000 in 2009. The second important trend is an increasing production of construction wood waste per housing start over the study period (Fig. 3). Between 1950 and 1954, some 812 kg of structural wood waste was produced on average for each housing start. For the period 2006 to 2010, this value increased to an average of 1,287 kg per house constructed, equivalent to a 1.6-fold increase. The principal driver for this increase appears to be the greater floor area of modern US single family homes. The average house area in the early 1950s was 101 m^2, whereas it averaged 227 m^2 for the period 2006 to 2010, equivalent to a 2.2 times increase in area. The third major trend is an increase in the proportions of engineered wood products (EWPs) and OSB present in these wastes. The model revealed that OSB and EWPs accounted for 34.2 percent of construction wastes in 2010, whereas they were absent from waste produced in 1950. In contrast, the proportion of lumber in these wastes decreased from 96.4 percent in 1950 to 62.8 percent in 2010 (Table 1).

The higher densities of OSB and EWPs compared with lumber (Intergovernmental Panel on Cimate Change [IPCC] 2006) and the change in the composition of the construction waste explains the remainder of the increase the mass of construction waste produced per start.

Net product consumption

The net product consumption of structural wood products into US single family homes is presented in Figure 4. The data have been calculated on a mass of product per finished floor area basis to clearly illustrate the temporal changes in wood product consumption irrespective of the increase in single family home size with time (Wilson and Boehland 2005). The lumber data in Figure 4 have been reduced by a factor of 10 to show clearly the trends in consumption for each structural wood product.

Three major trends are evident in Figure 4. First, since the early 1980s, OSB has substituted for plywood, and it became the predominant structural panel product in 1994. These data also indicate that, on the basis of area constructed, OSB appeared to have saturated the single

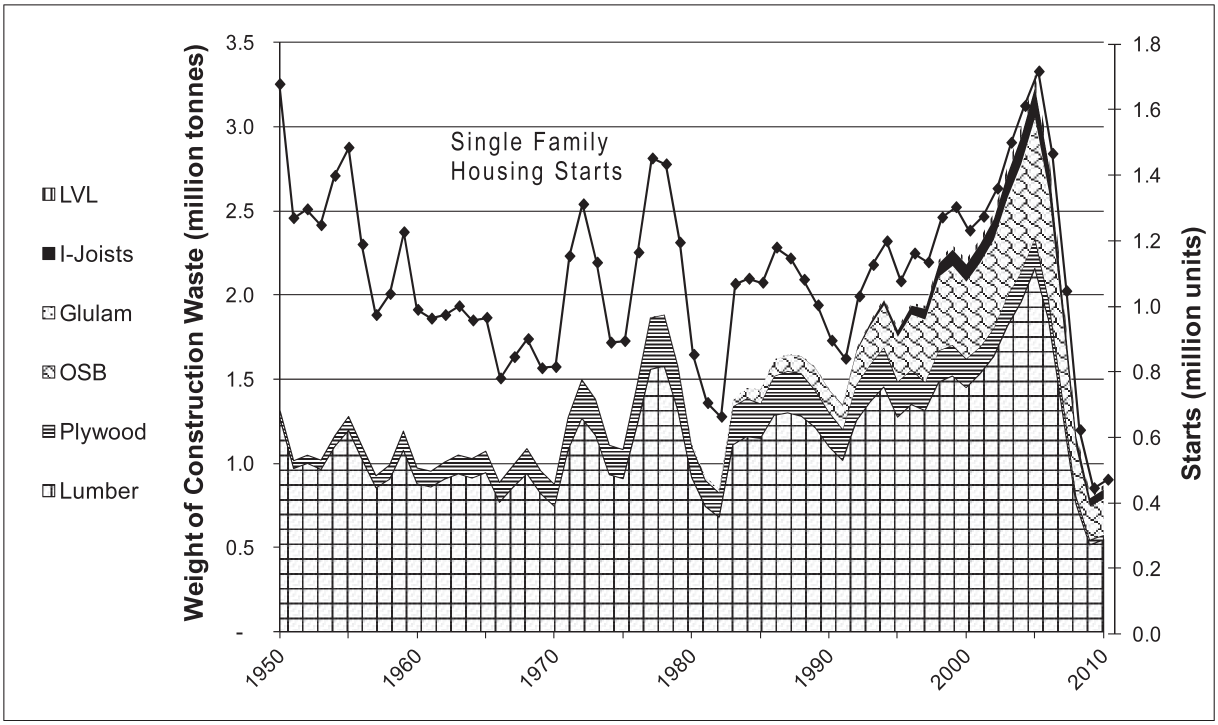

Figure 3.—Construction waste flows from single family home construction in the United States between 1950 and 2008 (Franklin Associates 1998; Howard 2003; Wood Products Council 2005, 2009; Fuller 2007; McKeever 2009; US Census Bureau 2009, 2011; US Environmental Protection Agency 2009a).

Table 1.—Changes in proportions of structural wood products in construction product waste between 1950 and 2010.

Year	Proportions of SWPs in total construction waste (% of total demolition waste in given year)[a] Lumber	Plywood	OSB	Glulam	I-Joists	LVL	Total demolition waste (million tonnes/y)
1950	96.4	3.6	0.0	0.0	0.0	0.0	1.32
1960	90.4	9.6	0.0	0.0	0.0	0.0	0.98
1970	85.1	14.9	0.0	0.0	0.0	0.0	0.88
1980	82.1	16.5	0.9	0.5	0.0	0.0	1.12
1990	76.3	14.1	8.6	0.5	0.3	0.3	1.45
2000	65.7	7.7	20.3	0.5	4.6	1.3	2.21
2010	62.8	3.1	24.5	0.6	6.2	2.8	0.87

[a] SWP = structural wood product; OSB = oriented strand board; glulam = glue laminated timber; LVL = laminated veneer lumber.

family housing market at about the end of the millennium. Second, softwood lumber has consistently been the predominant structural wood product. However, lumber has experienced the second largest decrease in usage intensity (after plywood) in US housing construction. This trend has been especially evident since the late 1980s. In 1986, builders used 95 kg of lumber for each square meter of floor area constructed, and this value had decreased to 52 kg/m^2 by 2010, a 45 percent reduction. I-joists and LVL are the two main wood products that have substituted for softwood lumber. I-joists have been used mainly in floor framing applications, whereas LVL has replaced some lumber in header applications (Garth et al. 2004).

Third, the net consumption of structural wood products has decreased from 119 kg/m^2 constructed in 1986 to 82 kg/m^2 in 2010, a 31 percent reduction. There has been a long-term trend for more modern structural wood products, such as OSB, I-joists, and LVL to replace the traditional lumber and plywood products. These developments have resulted in the structural needs of the US single family housing industry being met by a smaller mass of structural wood products per unit area constructed.

Demolition product wastes

Between 1950 and 2010, the structural wood product demolition product waste emitted from single family homes increased almost 10-fold from 512,000 tonnes to approximately 4.5 million tonnes (Fig. 5). The trend line shows a steady increase that is substantially different from construction waste flows (Fig. 3). The shape of the construction waste curve is principally related to the annual number of housing starts, whereas demolition waste flows are strongly influenced by the number of houses in the stock and their half-lives.

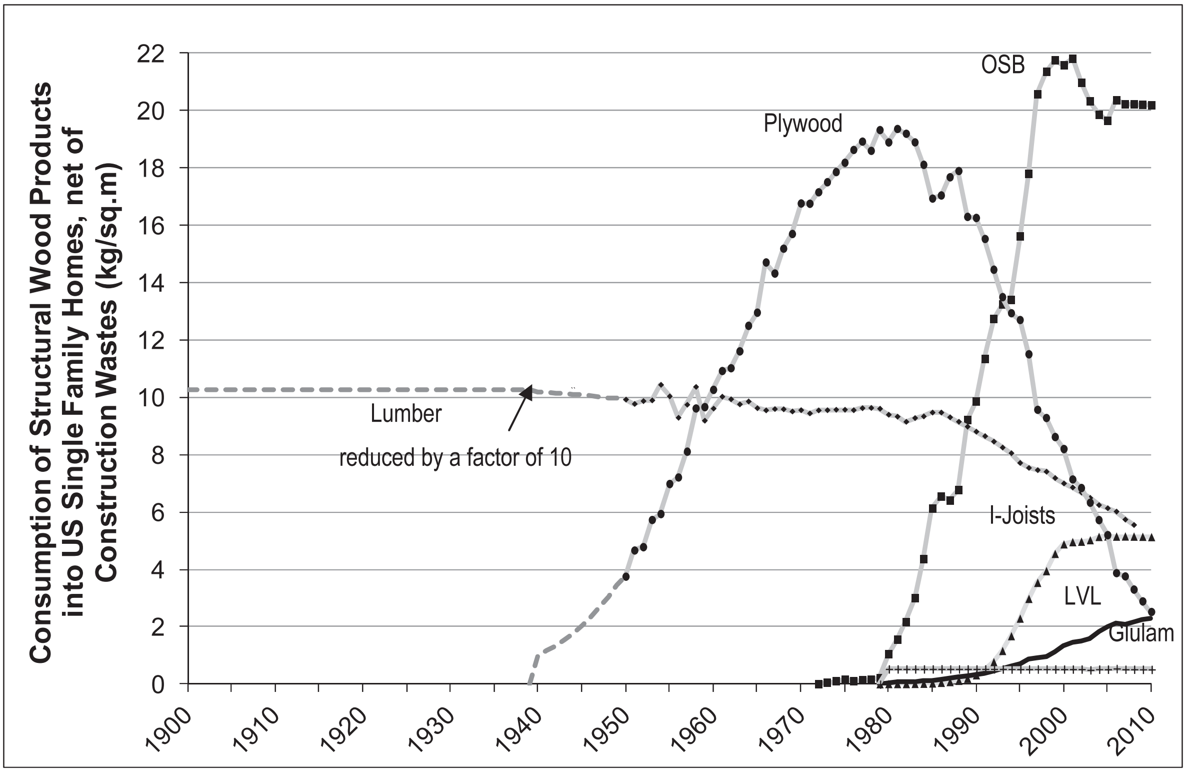

Figure 4.—Net product consumption of structural wood products per square meter constructed (Franklin Associates 1998; Howard 2003; Wood Products Council 2005, 2009; Fuller 2007; McKeever 2009; US Census Bureau 2009, 2011; US Environmental Protection Agency 2009a).

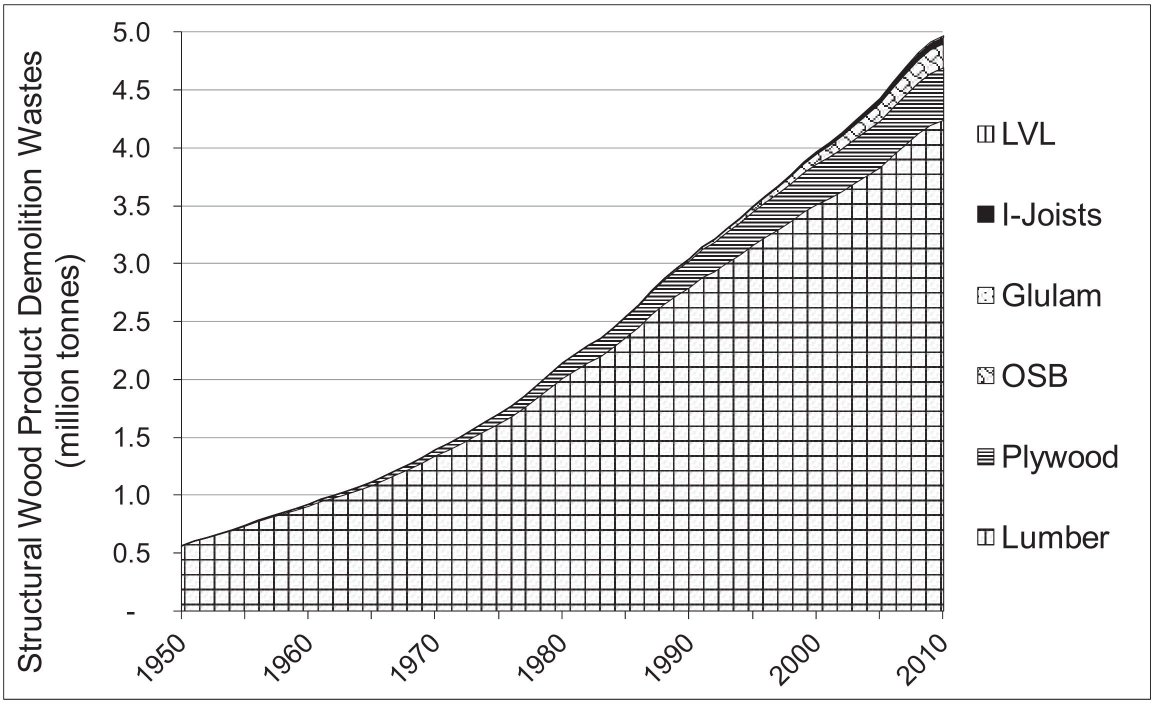

Figure 5.—Demolition product waste resulting from the removal of single family homes in the United States between 1950 and 2010 (Franklin Associates 1998; Alexander 2000; Howard 2003; Wood Products Council 2005, 2009; Fuller 2007; McKeever 2009; US Census Bureau 2009, 2011; US Environmental Protection Agency 2009a).

Several product-specific trends are also apparent in Figure 5. Before 1950, the demolition waste stream consisted essentially of lumber. Subsequently, plywood and, to a lesser extent, OSB and EWPs have become increasingly important components of demolition waste. OSB and EWPs share of the demolition product waste has increased from 0.7 percent in 1990 to approximately 5.8 percent of the 4.5 million tonnes emitted in 2010 (Table 2).

Model validation

Validation of the national stocks and flows model's outputs is difficult because there are no equivalent product-specific published data that may be used for a comparison. However, there are literature values that may be used to compare the total wood product flows calculated by the model for construction and demolition wastes. The following sections assess the validity of the construction waste, demolition waste, and net product stock estimates.

Validation using construction waste data.—Two publications have estimated the production of construction wood waste from single family homes (Ince and McKeever 1995, McKeever 2004), and one article provided an estimate of residential wood construction waste generated by single family and multifamily homes combined (Sandler 2003). In addition, Franklin Associates (1998) estimated that wood products constituted 42.5 percent of residential construction waste. In order to compare these studies with the data generated by the model (Fig. 3), the results of Sandler (2003) and Franklin Associates (1998) were modified to estimate a value for construction wastes emanating only from single family construction (US Census Bureau 2009, 2011) and to account for only structural wood products (McKeever 2009).

Each of the studies cited incorporated some uncertainty into its data. Wood waste data have not been collected at a national level, and therefore each study derived its estimates from existing information sources. The sources cited incorporated the following information into their approach to estimate construction waste flow information:

- Ince and McKeever (1995), point source sampling and housing starts;

Table 2.—Contribution of various structural wood products to demolition product waste flows by decade.

	Proportions of SWPs in total demolition product waste (% of total demolition product waste in given year)[a]						Total demolition waste (million tonnes/y)
Year	Lumber	Plywood	OSB	Glulam	I-Joists	LVL	
1950	99.4	0.6	0.0	0.0	0.0	0.0	0.51
1960	97.5	2.5	0.0	0.0	0.0	0.0	0.84
1970	95.6	4.4	0.0	0.0	0.0	0.0	1.26
1980	93.1	6.9	0.0	0.0	0.0	0.0	1.94
1990	91.0	8.3	0.6	0.1	0.0	0.0	2.76
2000	87.5	9.6	2.4	0.1	0.3	0.1	3.61
2010	84.3	9.9	4.6	0.2	0.8	0.3	4.53

[a] SWP = structural wood product; OSB = oriented strand board; glulam = glue laminated timber; LVL = laminated veneer lumber.

Table 3.—Comparison of published residential structural wood construction waste and those estimated by the stocks and flows model.

Year	Single family structural wood construction waste (million tonnes)		% difference (from model estimate)	Reference
	Published estimates	Model estimates		
1993	2.30	1.85	20	Ince and McKeever (1995)
1996	2.04[a]	1.96	4	Franklin Associates (1998)
1998	2.64[a]	2.21	16	Sandler (2003)
2002	3.13	2.49	21	McKeever (2004)

[a] Adjusted literature data due to single family and multifamily construction wood wastes being mixed.

- Franklin Associates (1998), economic expenditure, sector information, and point source sampling;
- McKeever (2004), national levels of construction activity and population data; and
- Sandler (2003), composition studies, sector information and expert opinion.

The different methods used for generating these results show clearly that there is no standard method for estimating construction waste quantity and composition. Another challenge is that, aside from Franklin Associates (1998), these publications do not all explicitly present their methods of extrapolation, making it difficult to assess the reasons for the disparities between the published wood construction waste estimates and those produced by the stocks and flows model.

Despite these challenges, the single family housing stocks and flows model outputs compare reasonably well to published construction waste data (Table 3). Values calculated by the model are within 21 percent of previously estimated values. In addition, the wood construction waste flows determined by the stocks and flows model are linked to the initial consumption of the wood products. Previously reported estimates do not contain this level of detail, nor is it apparent that their estimates associate waste production and product consumption. This difference, in conjunction with the consistently lower estimate provided by the model, may suggest that those estimates found in the literature have overestimated the structural wood construction waste emitted from the US construction sector.

Validation using demolition waste data.—The few existing published estimates of demolition wood waste flows incorporate a wide range of information sources and assumptions. For instance, the national demolition waste estimates for 1993 were extrapolated from a single regional study of New York (Ince and McKeever 1995). In contrast, the 1996 estimates were developed from a study of three single family homes in Portland, Oregon, and a single multifamily unit in Maryland, and uniform floor areas of 1,600 ft^2 and 1,000 ft^2, respectively, for each dwelling type were also assumed (Franklin Associates 1998). The methods used to calculate the 1998 estimates were not described in detail, but the publication does refer to the use of composition studies, sector information, and expert opinion to generate estimates (Sandler 2003).

Although each publication's authors acknowledge the considerable uncertainty contained in their estimates (Ince and McKeever 1995, Franklin Associates 1998, Sandler 2003), these data are the best available information with which to validate the stocks and flows model. The wood material data used in each of these studies were collected largely in the colder northern US states, a region that has been reported to have a higher intensity of wood usage in residential construction (McKeever and Anderson 1992, Wilson 2006). In addition, the 1993 and 1998 demolition disposal estimates have been cited as potentially overstating the wood content of the wastes by underestimating concrete disposal as a result of the use of a flawed C&D landfill disposal estimation methodology (Franklin Associates 1998, Sandler 2003, Athena 2007). Some manipulation of the data produced was required to develop wood demolition waste values from Franklin Associates (1998) that could be used for validation because it did not directly determine a national demolition wood waste estimate. The report did contain composition studies from six residential demolitions, of which the average composition included 41 percent wood products. This figure was used to refine a demolition wood waste estimate from Franklin Associates (1998). Any further efforts to refine published wood demolition figures and compare them with model outputs was considered speculative because the distribution of single family to multifamily homes or structural to nonstructural wood products is not known.

It was therefore considered that the disparities between the published demolition wood waste values and the model outputs presented in Table 4 may be largely explained by differences in the study boundaries and the methodologies used. As discussed earlier, published studies

- included multifamily homes,
- extrapolated national values from northern regional point samples that embody a larger scope of nonstructural wood products, and
- calculated data from simplified residential demolition estimation models.

Another cause of the disparity between figures is that the removal rate of homes from the stock used by the single family housing stocks and flows model may be conservative. The values used by the model are based on regression of US Census housing stock data, and while the half-lives of older buildings were similar to those of other publications (Winistorfer et al. 2005, Skog 2008), newer houses exhibited much longer half-lives (McFarlane et al., submitted for publication). The use of a longer average half-life would reduce the flow of demolition wastes.

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 material removed by demolition. The estimates of the net product stocks from 1950 to 2010 are shown in Figure 6, and the changing proportions of structural wood products in US single family homes are presented in Table 5.

Table 4.—Comparison of published residential wood demolition waste flows and those estimated by the stocks and flows model.

Year	Wood demolition waste (million tonnes)		% difference	Reference
	Published estimates	Model estimates		
1993	18.3[a]	3.00	84	Ince and McKeever (1995)
1996	6.41[a,b]	3.26	49	Franklin Associates (1998)
1998	5.47[a]	3.43	37	Sandler (2003)

[a] Adjusted literature data due to single family and multifamily construction wood wastes being mixed.

[b] Calculated from total residential demolition waste using an assumed 41 percent wood composition.

The model estimated that approximately 1,220 million tonnes of structural wood products had accumulated in single family homes in the US by 2010. The net product stock also demonstrated the gradual substitution of softwood lumber and plywood by OSB and EWPs, which by 2010 had increased their proportions to approximately 10.6 percent of the stock of structural wood products in US single family residences (Table 5).

There was only one known value in the literature with which to calibrate the wood products stock estimation. In 2003, the carbon stored in the structural wood products in the US housing stock was estimated to be 528 Tg C (Wilson 2006). In order to obtain a comparable carbon stock value, data for 2003 obtained from the single family housing stocks and flows model were converted to a carbon equivalent value. The resultant value was 548 Tg C, which was 4 percent higher than the value estimated by Wilson (2006; Table 6). These values are comparable given the similarity in scope and the relative simplicity of Wilson's calculations, which were intended to provide a general sense of the magnitude of carbon stored in wood products used in US houses. The variables used in the calculation of this figure include the average carbon storage of 4.38 Mg for an average single family home and an estimation of 120.6 million total houses in the US stock in 2003 (Wilson 2006). Because Wilson (2006) applied a carbon storage value for single family homes to the total US housing stock, including single family and multifamily, it is plausible that Wilson's analysis resulted in an overestimation of the stock.

Another validation was undertaken by comparing the model's outputs to the estimate of harvested wood products (HWPs) in use published in the US Agriculture and Forestry Greenhouse Gas Inventory (US Department of Agriculture 2008). In 2003, the inventory of all HWP in use was 1,381 Tg C, which compares favorably with the single family housing stocks and flows model estimation of 654 Tg C in single family homes (Table 6).

HWP is the term used by the United Nations Framework Convention on Climate Change (UNFCCC) for wood products, and it is defined as ''wood-based materials that, following harvest, are transformed into commodities such as furniture, plywood, paper and paper-like products or used for energy'' (UNFCCC 2003). In essence, HWP includes all wood material (including bark) that leaves harvest sites (IPCC 2006), and HWPs in use consist of stocks of carbon with various half-lives. For example, fuelwood may be

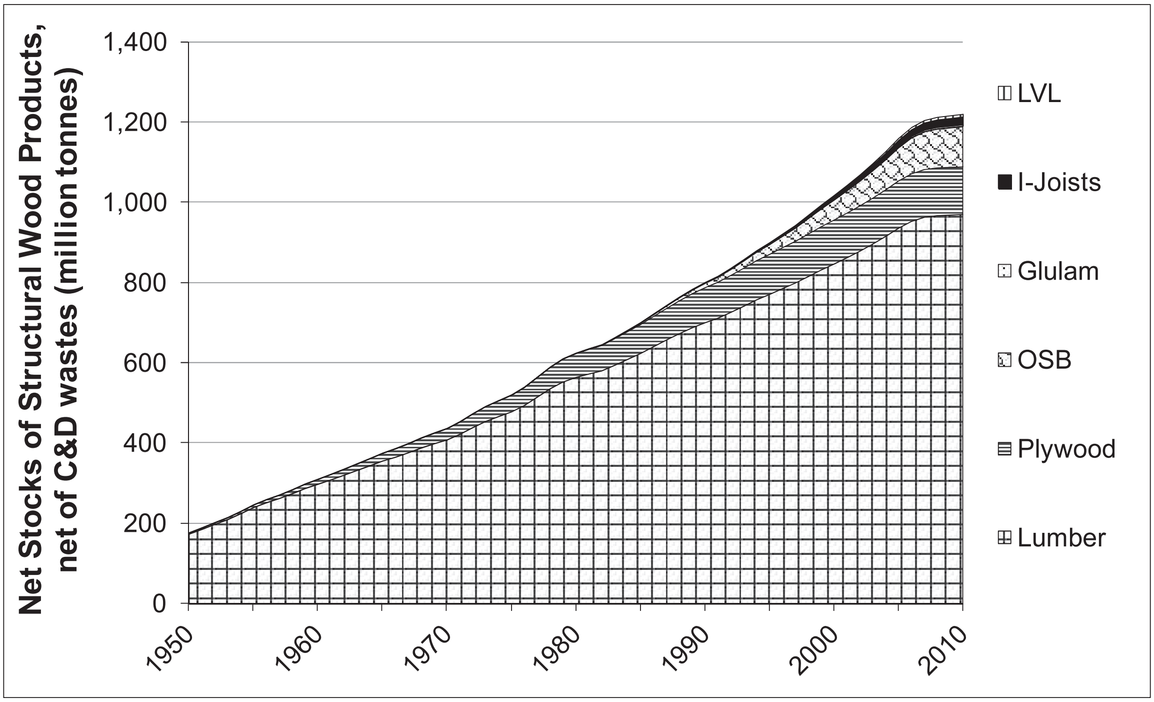

Figure 6.—Cumulative net product stock of structural wood products in single family homes in the United States (Franklin Associates 1998; Alexander 2000; Howard 2003; Wood Products Council 2005, 2009; Fuller 2007; McKeever 2009; US Census Bureau 2009, 2011; US Environmental Protection Agency 2009a).

Table 5.—Cumulative net structural wood product stock distribution changes, by decade.

Year	Proportions of SWPs (% of cumulative net product stock)[a]						Cumulative net structural wood product stock (million tonnes)
	Lumber	Plywood	OSB	Glulam	I-Joists	LVL	
1950	98.8	1.2	0.0	0.0	0.0	0.0	176
1960	96.2	3.8	0.0	0.0	0.0	0.0	310
1970	93.6	6.4	0.0	0.0	0.0	0.0	437
1980	90.4	9.6	0.1	0.0	0.0	0.0	624
1990	87.5	11.0	1.3	0.1	0.0	0.0	800
2000	83.2	10.9	4.9	0.2	0.6	0.2	1,017
2010	79.5	9.8	8.2	0.3	1.6	0.6	1,220

[a] SWP = structural wood product; OSB = oriented strand board; glulam = glue laminated timber; LVL = laminated veneer lumber.

converted to CO_2 the year it is harvested, paper products usually have half-lives in the range of 5 years, and structural wood products may have half-lives of decades to more than 100 years (IPCC 2006). Given this definition, it may be reasonable to expect that structural wood products in single family homes in the US account for approximately half of the total HWPs in use. Unfortunately, there are no published values that may be used for a more detailed comparison.

These validation exercises suggest that the single family housing stocks and flows model provides reasonable estimates of the structural wood products stored in single family homes in the United States.

Evaluation of assumptions

Several assumptions were made in order to estimate structural wood product stocks and flows. In order to understand how each of these assumptions affected the model outputs, sensitivity analysis of the major assumptions was undertaken. The key findings are summarized below.

Implications of excluding renovation activities.—Renovation activities consume construction products and produce both construction and demolition wastes. From 1950 to 2006, renovation activities were estimated to account for approximately 30 percent of the total lumber and structural panels consumed in residential structures, which included single family, multifamily, and manufactured homes (McKeever 2009). Specifically, 31 percent of the lumber (including softwood and hardwood) and 29 percent of the structural panels (including plywood and OSB) were consumed in renovation activities (McKeever 2009). However, this study and other investigations did not provide data on the specific structural wood products used to renovate single family homes (Ince and McKeever 1995, Franklin Associates 1998, Sandler 2003, US EPA 2009a). There was also inadequate information on the original year of construction for residences being renovated, which is also required by the model.

This lack of data made it impractical to develop a module of the model that accounted for individual structural wood products consumed and wastes produced by the renovation of single family homes. The absence of such a module does not greatly limit the model's utility. In general, the majority of renovation activities does not create a change in structural wood product stocks and flows because more than 80 percent of renovations are nonstructural and address the addition or replacement of envelopes, amenities, and infrastructure, such as wiring and plumbing (US Census Bureau 2009). Thus, stocks and flows associated with renovation activity were excluded from the model.

Excluding renovation wastes from the model does not affect its construction waste estimates, because only emissions resulting from new construction are considered by the model. 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 waste estimates. The amount of demolition product waste will be slightly underestimated, since approximately 3 percent of renovation activities are associated with the additional construction of residential square area (US Census Bureau 2009). The composition of wood products present in demolition wastes are also likely to vary slightly because renovation will replace some structural assemblies with different products.

Sensitivity analysis

The sensitivity analysis assessed the significance of six major assumptions on the outputs of the single family housing stocks and flows model. The assumptions evaluated are presented in Table 7. The value associated with each assumption was varied by ±10 percent, and the impact of this change was evaluated for model outputs for total construction waste, total demolition product waste, and total cumulative net product stock. In each case, ''total'' refers to the sum of all of the structural wood products.

Sensitivity analysis results.—The sensitivity analysis revealed several important points regarding the assumptions that most significantly affected the single family housing stocks and flows model. It also provided useful insights into which parameters should be collected most accurately in order to increase the precision of the model.

Estimates of total construction waste were very 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.

Table 6.—Comparison of published values of carbon stored in single family (SF) residences and harvested wood products (HWPs) in use and those estimated by the stocks and flows model.

Year	Parameter	Published estimate (Tg C)	Model's estimate (Tg)	Difference (%)	Reference
2003	Structural wood in SF homes	528	548	−4	Wilson (2006)
2003	HWP in use	1,381	548	60	USDA (2008)

Table 7.—Model assumptions tested in the sensitivity analysis.

Assumption reference	Description
A	Weight of construction waste produced per m^2 constructed
B	Wood waste as a percentage of total waste produced per m^2 constructed
C	Estimates of gross product consumption for glulam per m^2 constructed
D	Estimates of gross product consumption for I-joist per m^2 constructed
E	Estimates of gross product consumption for LVL[a] per m^2 constructed
F	Removal rate of single family home finished floor area from the stock

[a] LVL = laminated veneer lumber.

Total demolition product waste values were most sensitive to the removal rate of finished floor area from the stock (Assumption F). This sensitivity was followed by the amount of construction waste being produced per square meter constructed (Assumption A) and the amount of wood present in the total construction waste (Assumption B; Fig. 7).

The cumulative net product stock values were most 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; Fig. 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 percent 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 percent did not affect any of the total construction waste, demolition product waste, and cumulative net product stock variables.

In order to develop more precise estimates of wood products stocks and flows, it is therefore important that efforts be focused on collecting improved information on model input parameters A, B, and F in Table 7. Further studies should therefore better quantify the mass of wood waste (by product type) generated per unit area constructed and the half-lives of single family homes.

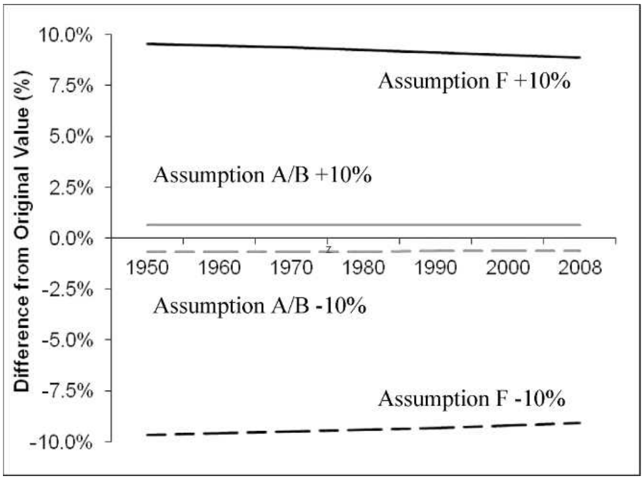

Figure 7.—Sensitivity of total demolition product waste to various parametric inputs.

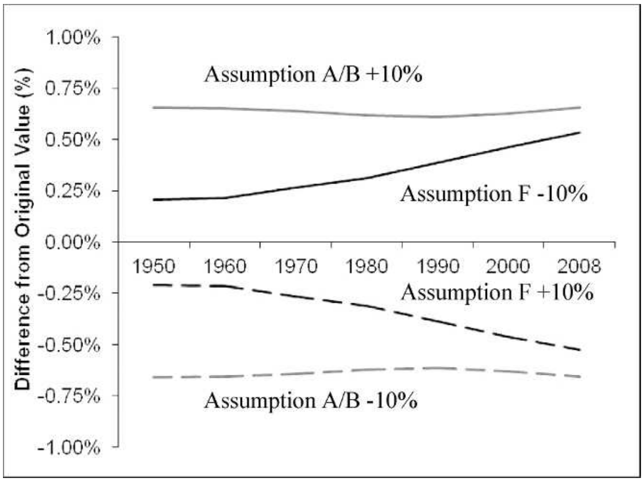

Figure 8.—Sensitivity of total cumulative net product stock to various parametric inputs.

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 2010. This national model's results were expressed through six variables—gross product consumption, construction product wastes, net product consumption, demolition product wastes, net product stocks, and cumulative net product stocks—for six structural wood products—softwood lumber, softwood plywood, OSB, glulam, I-joists, and LVL.

After being introduced in the 1970s and early 1980s, EWPs and OSB have substituted for lumber and plywood, respectively, in the product stock of single family homes and from 1986 to 2010 there was a 31 percent reduction in the mass of structural wood products consumed per unit floor area constructed. By 2010, the amounts of OSB and EWPs in total construction waste, cumulative net product stock, and demolition product waste increased, respectively, to 34.2, 10.6, and 5.8 percent of wood product mass per unit area constructed. The model showed clearly the substitution occurring at the product level and the delay in these products being released as demolition waste. The changing product distribution immediately impacted the construction product wastes, and then the cumulative product stock, before finally being released as demolition product wastes.

The main challenges in developing this single family housing 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 most strongly influenced by assumptions regarding the mass of waste produced per square meter constructed, the proportion of total construction waste that was wood, and the removal rates of single family homes from the stock. More accurate information therefore needs to be collected on construction waste production and on the percentage of wood products within these wastes. It is also demonstrated that improved estimates of single family homes' half-lives is required.

The outputs of the single family housing stocks and flows model quantify a causal link between the consumption, stocks, and wastes of structural wood products through single family residences in the United States. This type of information is becoming increasingly valuable because it has the potential to 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.

Appendix

Data sources

Data on US single family home floor area and stocks and starts were obtained from the US Census Bureau (2011). Because no data were available between 1900 and 1950, the average finished floor area for this period was assumed to be that in 1950 (i.e., 99 m^2). This is likely to be an overestimation, because an extrapolation of historical data indicates that single family housing floor areas probably increased between 1900 and 1950.

The model was therefore considered to slightly overestimate the amount of structural wood products stocked into single family homes constructed before 1950.

The gross product consumption data were 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 data sets. Complete data sets were available for softwood lumber, softwood plywood, and OSB usage in single family homes in the US between 1950 and 2006 (McKeever 2009). This report combined published estimates with economic data and use factors in order to develop consistent wood construction product consumption estimates for the United States over the period (McKeever 2009).

Because there were no sources for data on structural wood product consumption prior to 1950, the model applied the 1950 figure (i.e., 0.23 m^3/m^2 constructed) to all single family homes built between 1900 and 1949 (McKeever 2009). It was also assumed that lumber was the only structural wood product being consumed between 1900 and 1940, when plywood was introduced (APA 2009).

In order to estimate consumption for 2007 to 2010, 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 missing data for I-joists and LVL between 1980 and 1996, as well as 2007 to 2010.

There was a shortage of data on the consumption of glulam by single family home construction. Two Wood Product Council reports provided information on glulam usage in 2003 (WPC 2005) and 2006 (WPC 2009), and these data were converted into consumption on a square meter of single family home constructed basis. The average material use intensity of these two periods was assumed for all years between 1980 and 2010 (C. Adair, The Engineered Wood Association, Tacoma, Washington, personal communication, 2009).

The demolition product waste parameter was calculated as follows. The historical net product consumption of structural wood product data were combined with housing starts, average floor area, and a calculated removal rate in order to determine the mass of structural wood products emitted as waste from the demolition of homes for each year between 1900 and 2010. It was assumed that the net amount of wood products consumed in construction remained until demolition when they were completely extracted as demolition product waste (Franklin Associates 1998).

The demolition product waste model required data on the removal rates of single family homes from the housing stock. Half-lives of US single family homes published by McFarlane et al. (submitted for publication) were used. These half-lives were calculated from the biannual US Censuses, which track residence stocks by decade of construction. In all, data from 13 biannual US Censuses from 1985 to 2009 were compiled, and regression analyses were undertaken to determine house half-lives by decade. US Census data have been considered to be the most accurate data source to calculate the removal rate of homes from the stock (Wilson 2006, Belsky et al. 2007).

The model was validated by comparing outputs with published data. In two instances, the validation process required the conversion of wood product mass data to carbon equivalents using IPCC default carbon densities (IPCC 2006). Lumber and glulam data were converted using a carbon factor of 0.5 kg C/kg, and all panels other than EWP were converted using a value of 0.468 kg C/kg wood product.

Recommendations

The main sources of data from the literature used in this single family housing 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 (i.e., 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 stocks and flows data are modeled at four spatial scales: individual building, regional level, state level, and national level (National Academy of Sciences 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 to contribute to decision making in the sustainable use of materials by the construction industry.

Furthermore, although this article 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 (i.e., including but not limited to drywall, metals, plastics, roofing, rubble, brick, glass, miscellaneous) 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.

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