Source Evaluation of Solid Waste in Building Construction

By Rafael M. Gavilan[1] and Leonhard E. Bernold,[2] Member, ASCE

Abstract: The construction industry contributes a major portion of the waste stream in the United States. Both increased environmental awareness and increased cost for depositing waste have caused many construction companies to reevaluate their practices. So far, no scientific data are available for developing strategies to adjust to the changing parameters and requirements. This paper addresses one critical step in developing a comprehensive waste-management system; the categorization and quantification of construction wastes. Several residential-building projects were used to test a conceptual framework for studying the sources of solid wastes in one important segment of the construction industry. Three important categories of building materials—brick and block, dimensional lumber, and Sheetrock—were analyzed using a "sources-of-waste" framework. The presented research data indicate that solid wastes in residential construction are primarily scraps resulting from cutting dimensional stock material (e.g., lumber) to size. As will be shown, many factors are related to the amount of such process waste. Strong relationships between poor productivity and high waste generation are suggested.

Introduction

Construction and demolition (C&D) wastes account for a significant portion of America's municipal solid-waste stream. Some studies estimate rates as high as 23% (Apotheker 1990). Old C&D landfills are quickly being filled, and space for new ones is growing scarce. New knowledge about the toxicity of certain construction materials (such as treated lumber) has caused a marked increase in C&D landfill tipping fees. Meanwhile, both the construction industry and the public are growing increasingly more concerned about raw material shortages and the impact of everyday activities on our environment.

In spite of these alarming conditions, very little detailed knowledge currently exists about the origins and distribution of construction wastes. The combination of these factors warrants that present waste-management methods in construction be reevaluated. More important, the origins of construction wastes should be studied to determine the most effective methods for dealing with these wastes at their source. Although construction managers must by necessity always attempt to optimize resources and thus minimize waste, construction-material wastes are not considered an important variable in the cost equation. Part of the problem stems from the long-held perception that waste "is suggestive of something which has no value and which the junkman can take away—in other words, something which a company is willing to sell if it can get anything for it, but which, if not, it is willing even to pay somebody to haul away" (Leenders et al. 1990). Illegal dumping of construction wastes is evident in many places and has reached epidemic

[1]Captain, Savannah District Army Corps of Engrs., P.O. Drawer 610, Warner Robins, GA 31099-0610; formerly, Grad. Student, Dept. of Civ. Engrg., North Carolina State Univ., Box 7908, Raleigh, NC 27695.

[2]Assoc. Prof., Dept. of Civ. Engrg., North Carolina State Univ., Raleigh, NC.

Note. Discussion open until February 1, 1995. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on June 15, 1993. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 120, No. 3, September, 1994. ©ASCE, ISSN 0733-9364/94/0003-0536/$2.00 + $.25 per page. Paper No. 6363.

proportions in some Northeastern states (Spencer 1989). This may indicate that the concept of managing waste is a fairly new one to both legislators and the construction industry. Illegal dumping signifies a disregard for the law and the environment. It also signifies that lawmakers may have given at least some members of the industry the perception that no other viable disposal alternative was available.

On another level, many projects are under way to find better ways to reuse material (Knapp 1992), to search for new methods of recycling waste economically (Kalin 1991; Spencer 1990), to study the impact of incineration (Schaub 1990), and to find ways to reduce the amount of generated waste (Castledine 1990; *Waste* 1990). The reduction of waste at its source is genuinely the most logical and even most economical way to "treat" construction waste. Practical waste-reduction strategies require a detailed understanding of what causes construction waste. First, however, a clear definition of construction waste is needed. The next section will introduce a general definition before reviewing earlier attempts to classify and quantify solid waste in construction.

DEFINITION OF CONSTRUCTION AND DEMOLITION WASTES

Tchobanoglous et al. (1977) provides one of the more general definitions of construction and demolition wastes: "Wastes from razed buildings and other structures are classified as demolition wastes. Wastes from the construction, remodeling, and repairing of individual residences, commercial buildings, and other structures are classified as construction wastes. These wastes are often classified as rubbish. The quantities produced are difficult to estimate and variable in composition, but may include dirt, stones, concrete, bricks, plaster, lumber, shingles, and plumbing, heating, and electrical parts." In an effort to discourage landfilling and to promote reuse and recycling, some states have mandated the segregation of C&D wastes. These mandates, in turn, have led to very narrow definitions of C&D wastes. Many states do not now consider land-clearing debris (e.g., stumps) and yard wastes (i.e., grass clippings, tree limbs, and leaves) part of the C&D waste stream. Moreover, some states define brick, block, and concrete wastes not as C&D wastes but as "inert debris."

Because the study presented in this paper focused specifically on the waste created during actual construction of the structure, the definition of construction and demolition wastes from Tchobanoglous et al. (1991) will be used. First, however, the published attempts to quantify the C&D waste stream should be reviewed.

CLASSIFICATION AND QUANTIFICATION MODELS

Data about C&D wastes range from very broad categorizations to empirically derived construction-waste–generation rate models. An extensive literature search revealed that work in the area is generally scarce. Discussions with project managers and waste-management engineers, however, indicate that some members of the construction industry (as well as several private engineering firms) have made some recent progress.

Spivey (1974b) documented one of the earliest efforts to categorize construction wastes. He classified the most common components of work-site wastes as follows: (1) Demolition materials (i.e., concrete, brick, wallboard, plaster, and used lumber); (2) packaging materials (i.e., paper, cardboard, plastic, excelsior, and metal retaining bands); (3) wood (including trees and

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scrap lumber); (4) waste concrete and asphalt; (5) garbage and sanitary waste; (6) scrap-metal products; (7) rubber, plastic, and glass; and (8) pesticides and pesticide containers. Spivey's work is further discussed later in this paper.

Several other efforts have been undertaken in the past to quantify the components of C&D debris. Wilson et al. (1976) attempted to quantify the constituents of demolition wastes as early as 1976. A study conducted at the Massachusetts Institute of Technology in 1979 found a correlation between the size of a municipality and its per capita construction-waste–generation rate (Keller 1992). The correlation, however, was only valid on a very general level, and therefore, did not have much predictive value. Another study, conducted by Roy F. Weston, Inc., Burlington, Mass., confirmed that waste-generation rates are related to population levels. However, the study also concluded that these rates will fluctuate depending on the local level of construction activity and on any "extraordinary" projects in the area (Keller 1992). Furthermore, the Toronto Home Builders Association was able to quantify the components of the waste resulting from residential construction (Apotheker 1990). Their results are presented in Table 1.

As depicted in Table 1, dimensional lumber, drywall, and masonry and tile account for over half of the construction wastes generated during residential construction. Unfortunately, the great variety in the types of construction make it difficult to call these findings representative of the entire industry. Construction firms that specialize in commercial construction, for example, would probably have an entirely different waste-stream composition.

Interestingly, a literature search did not surface any data related to the sources of construction wastes. Moreover, few data are available to help predict the amounts or types of wastes generated during construction operations. Work-site visits and interviews showed that experienced construction managers know roughly how much waste they will create during a given

TABLE 1. Constituents of Waste Stream in Residential Construction (*Making a Molehill* 1990)

Material (1)	Volume (%) (2)	Average weight per house (kg) (3)
Dimensional lumber	25	845
Drywall	15	Not available
Masonry and tile	12	1,000
Manufactured wood	10	424
Old corrugated containers	10	705
Asphalt	6	Not available
Fiberglass	5	Not available
Metal waste	4	Not available
Plastic and foam	4	Not available
Other packaging	4	Not available
Other wastes	5	Not available
Total	100	—

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project. How efficiently this institutional knowledge is used across the industry is difficult to ascertain.

The next section reviews some currently available waste-management tools for the construction industry. The discussion will focus on the general approaches available to builders to help them develop integrated waste-management strategies.

CONSTRUCTION-WASTE–MANAGEMENT PRINCIPLES AND SYSTEMS

Most decision-making models include a step where the various alternative solutions to a problem are evaluated and ranked according to some predetermined criteria. In environmental decision making, this step is usually covered by an environmental impact assessment (EIA). EIAs are often used to gauge the impact of construction projects or activities on the environment (Black 1981; Canter 1983; Clark 1981; Munn 1983). Although EIAs are commonly used in planning construction projects, their scope is really too large for making construction-waste–management decisions. As now used, EIAs are tools for decision makers who are echelons above project managers and construction foremen. It is very difficult to quantify the effects of the typical decisions made by project managers and foremen at the work site on the pertinent "socio-ecological factors" (e.g., issues of flora and fauna). EIAs as currently used are therefore too broad to be of value in managing solid wastes on construction sites.

Early Construction-Waste–Management System

Spivey (1974a) was among the first construction engineers to see the need for construction-waste–management systems. He was a pioneer in helping to develop construction-waste–management practices. Spivey devised the following four-step planning procedure to assist in "optimum disposal":

1. Evaluate the composition and estimate the volume of solid wastes that will be generated (including demolished structures).
2. Determine recycle potential (volume, markets, costs, and return).
3. Evaluate disposal options available (recycle, burial, and incineration).
4. Match disposal options to volume and composition of wastes considering economy, environmental protection, and resource depletion.

Additionally, Spivey went on to establish a waste-management hierarchy of recycling, incineration, and landfilling.

Spivey's work, well ahead of its time, did not directly address the issue of source reduction. Today, it is accepted that the single most effective way of dealing with any solid waste is not to create it in the first place.

MODELING GENERATION OF CONSTRUCTION PROCESS WASTE

It is apparent that the solid-waste stream is closely related to the material flow. Fig. 1 summarizes the many flow patterns of construction materials from the time they are delivered to the site until their final disposition. The term *consumable* is used to denote materials that will become part of the final structure, such as bricks, concrete, and reinforcing steel. The term *nonconsumable* refers to materials that aid in the construction process but

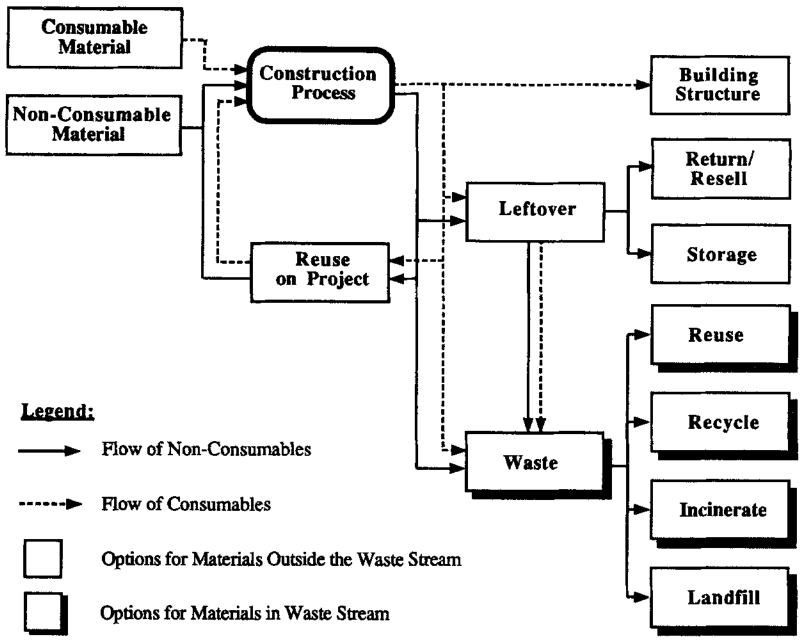

FIG. 1. Generic Flow Pattern of Construction Material on Site

do not end up as part of the building. These include materials used to build scaffolds, concrete forms, temporary retaining walls, and others.

As depicted in Fig. 1, construction materials generally end up in one of four dispositions: building structure, leftover, reuse on the same project, and waste. As indicated, leftovers may, and actually do very often do, end up as waste anyway because the other two options—resell and storage—are not considered or are found inconvenient. In addition, material suppliers many times will not buy material back if the base unit of delivery has been broken up (e.g., cube of bricks).

Also as indicated in Fig. 1, both consumables and nonconsumables may enter the waste stream after the completion of a construction process (e.g., framing). Data have not been found that quantify how much of the C&D waste stream consists of consumables, and how much consists of nonconsumables. Given the diverse nature of construction, the composition of C&D waste stream is expected to vary depending on the characteristics of the construction project and other parameters. As will be discussed later, these parameters range from local market forces to the skill level of the craftspersons involved in the project.

While the material-flow model presents a basic overview, it does not address the reasons why a material enters the waste stream, also called source identification. Source identification, however, is a first step toward reducing the amount of waste generated in construction.

Source Identification

The following is a conceptual framework that organizes the sources of construction waste into six categories.

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1. Design:

   - Blueprint error
   - Detail error
   - Design changes

2. Procurement:

   - Shipping error
   - Ordering error

3. Handling of materials:

   - Improper storage/deterioration
   - Improper handling (off-site and on-site)

4. Operation:

   - Human error (by craftsmen or other laborers)
   - Equipment malfunctions
   - Acts of God (catastrophes, accidents, and weather)

5. Residual:

   - Leftover scrap
   - Unreclaimable nonconsumables

6. Others not listed

It is assumed that the importance of these categories will vary not only from project situation to project situation but also from material to material. For example, it is more likely that concrete waste rather than dimensional-lumber waste will be created by design error.

Not all the listed errors will lead to construction wastes. Damaged or surplus materials can often be salvaged and reused or simply resold to the materials' vendor (*Costs* 1986). However, those wastes that are created can usually be attributed to shortcomings in one of the following areas:

Design

Two causes may lead to waste in this source category: design and detailing mistakes; and change orders. Design and detailing errors result from mistakes in engineering and design. If materials are purchased based on wrong design specifications, waste may result if they cannot be resold or returned to the vendor. The builder's only option may be to dispose of the materials. Moreover, if the builder already installed the material and is forced to take the flawed portion of the structure apart, he or she may not be able to salvage the materials. Again, waste may result. The same holds true for change orders. Additionally, supplier contracts are often signed and construction is begun before plans and designs are complete. Surplus materials are much more prevalent on these types of projects (*Costs* 1986).

Procurement

Errors in ordering and shipping can cause material wastes. Procurement mistakes can result in one of three material conditions: overshipment, undershipment, or misshipment. They are usually caused by miscommunication either within the builder's organization or between the builder and the vendor.

Handling of Materials

Improper handling or storage of construction materials can be a considerable factor in generating waste. Improper handling may occur at the work site, or before the material arrives at the site. That is, the material may be damaged during fabrication, packaging, loading, or delivery. Once at the site, construction materials may be damaged due to unnecessary rehandling or improper storage without appropriate protection. For example, many construction materials are subject to deterioration and biodegradation due to environmental impacts. Materials should be sheltered from environmental conditions and from biological agents (Knöfel 1978).

Operation

Specifically in building construction, the operations necessary to build the structures are closely related to the amount of generated waste. They can result from poor workmanship, or from acts of God. Poor workmanship may be caused by unskilled labor, inadequate tools and equipment, and/or poor working conditions (Oglesby et al. 1989). Acts of God include calamities during the construction phase such as earthquakes, work-site accidents, and poor weather.

Residual

Given present building techniques, some waste from the construction process is inevitable. These wastes include leftover material scraps from cutting stock-length material into shorter pieces to fit the design. It also includes pallets, packaging, and unreclaimable nonconsumables (such as sheet piles that cannot be recovered).

Other

These wastes may result from a wide variety of sources. Some builders have reported having to reorder construction materials because they cannot find the original order on the work site. When the original order is found, it may wind up as waste.

Selection of Project for Field Observations

Despite the U.S. economic recession in 1992, the Raleigh-Durham, N.C., area offered a wide variety of construction projects for field observations. Field observations began on July 10, 1992, and ended on August 18, 1992. This period will be called the observation window. The type of construction selected for observation was residential.

Residential construction was chosen over commercial, industrial, and highway construction because it offered some distinct advantages. First of all, residential construction sites were generally smaller. Given limited experience in this type of observation and no precedence from which to draw, it was imperative that the sites be easy to observe. A small work site affords the observer the opportunity to watch more activities at one time. Smaller work-sites, fewer crews working at one time, and the absence of heavy machinery and equipment are all factors that indicated the choice of residential construction would reduce the complexity of site observations. Additionally, the time available for field observations was limited and residential construction projects are generally shorter in duration.

With the help of the Raleigh Home Builders' Association, a total of five homes on four separate construction sites were chosen for observation. Table 2 summarizes some key characteristics of the projects. Two homes (A1 and A2) were built by the same builder on adjoining lots and are considered "one" project since it was not possible to separate the generated waste by building.

As indicated, four different styles of supervision were executed by four different builders; two small, one mid-size, and one large company. As will be shown, the size of the builder did not seem to have any impact on the amount of generated waste; even the type of supervision did not show any direct effect on waste production.

RESULTS OF FIELD OBSERVATIONS

This section presents the data that were gathered while observing the partial construction of the homes described. Commonalities in solid-waste generation are highlighted for three basic materials: masonry units, dimensional lumber, and Sheetrock. As will be discussed, the sources and quantities of solid waste not only are related to the observed material type but are also a function of the individual crew using that particular material (e.g., masons). The latter was one of the most significant lessons learned from field observations. Even though builders exert considerable influence over the activities on a work site, it is the subcontractor who can really make a contribution to reducing and intelligently managing construction wastes. That is, two subcontractors may produce vastly different amounts of waste for the same work. Corresponding to the three construction materials, the observations were limited to three phases of the construction phases: foundation, frame structure, and drywalls.

Foundation Wastes

Observation data should be viewed from different angles with each addressing a different set of questions. For that purpose, the collected data were organized in such a way as to allow both absolute and relative comparisons, not only between projects but also between materials or processes. Fig. 2 represents an example of a quantity-based comparison of foundation wastes between projects and a relative comparison of brick and block waste as a percentage of the total foundation waste.

As shown in Fig. 2(*a*), the total quantities of foundation wastes ranged from 3.05 m^3 (4 cu yd) on project D to 7.2 m^3 (9.4 cu yd) on project C. The data from project D reflect a project where the construction of the foundation was a particularly well organized and executed. Still, project A also generated significantly less waste per foundation than did projects B and C. One possible explanation for this is that project A's two homes had "simpler" foundations than those of the other projects. Project A's were the only homes without garages. Their foundations were simple rectangles with not as many "turns and corners" as the other projects' foundations. Contrary to a common expectation, however, the crew working on the fairly complex foundation of project D produced far less waste than the others. Through personal discussions, the observer found that the masons on this

TABLE 2. Characteristics of Observed Projects for Study

Parameters	Sites				
(1)	A1 (2)	A2 (3)	B (4)	C (5)	D (6)
Builder size[a]	small	small	mid-size	large	small
Home size (m^2)	121	121	344	325	325
Stories	1	2	2	2	2
Foundation	Block	Block	Block	Brick/block	Brick/block
Roof truss[b]	Stick	Stick	Stick	Prefab	Unknown
Waste-management strategy	23 m^3	23 m^3	19 m^3	23 m^3	To be determined
Superintendent involvement[c]	C	C	B	D	E

[a]Large builder, 100–300 homes per year; mid-size builder, 30–40 homes per year; and small builder, five to 10 homes per year.

[b]A stick truss means that the truss was fabricated on the site from dimensional lumber; a prefab truss means that the truss was prefabricated at some other location.

[c]Involvement scale: from A = low involvement (almost never present on site) to E = extremely involved (almost always present on site).

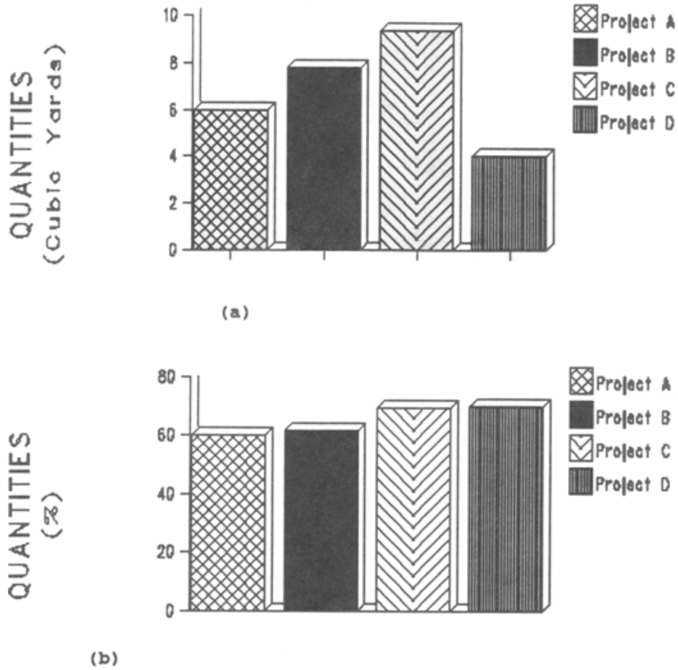

FIG. 2. Absolute and Relative Comparisons of Foundation Wastes by Projects: (*a*) Total Foundation Wastes; and (*b*) Brick and Block as Percentage of Foundation Wastes

site were very competent craftsmen who worked at a very deliberate pace. In fact, all intricate masonry work on this project was done by a two-man crew, consisting of a specific mason and one helper. Moreover, the project superintendent was almost always present on the site. His close supervision and attention to detail was key in the identification of potential sources of large amounts of waste on at least two separate occasions (Gavilan 1992).

Table 3 presents more detailed data about the foundation waste of project D. As shown in column (3), 70% of the foundation waste consisted of brick and block, which are considered consumables. The remaining 30% of foundation wastes were packaging wastes or wastes from nonconsumables. They consist of cement bags, plastic sheets that were used to cover the cement bags as protection, and banding material that stabilized the brick during transportation. Packaging wastes are discussed in greater detail by Gavilan (1992).

Table 3 also summarizes the identified sources of foundation waste for consumable materials according to the framework presented earlier. Since no equipment was used and no acts of God could be observed, these categories were not used. The same holds true for design and procurement errors. As indicated, 1.75 m^3 or 82% of the brick and block waste originated as residual process waste. That is, residual scrap resulting from the cutting of bricks and blocks to fit into turns and corners. The cut pieces were not reused and lay scattered on the floor after the foundation was complete. Another 14% of brick and block wastes resulted from improper materials handling. Based on the assessment of delivered cubes of bricks and blocks,

TABLE 3. Composition and Sources of Foundation Waste for Project D

Composition of Waste			Sources of Waste (m^3)			
Waste type (1)	Quantity (m^3) (2)	Percentage (3)	Process waste (4)	Poor materials handling (5)	Human error (6)	Other (7)
Bricks/blocks	2.14	70	1.75	0.3	0.09	0.0
Cement bags	0.3	10	Not available	Not available	Not available	Not available
Banding material	0.3	10	Not available	Not available	Not available	Not available
Plastic film	0.3	10	Not available	Not available	Not available	Not available
Total	3.04	100	—	—	—	—

it was determined that about 3% of the masonry units were broken before the first mason ever arrived on the site (Gavilan 1992). In other instances, leftover bricks were sometimes damaged when they were sloppily restacked. Craftsmen error accounted for another 4% of all brick and block wastes. In general, however, the masons on project D worked quickly and made very few mistakes.

As depicted in Fig. 2, 5.3 m^3 (7 cu yd) of foundation waste were created on average, with the quantity varying generally, but not consistently, with the complexity of the foundation. Of the total foundation waste, 60–70% consisted of brick and block units. The remainder was packaging materials. A breakdown of the sources of brick and block waste revealed that in general, 85% of that waste originated as process waste, 10% was damaged during delivery, and another 5% resulted from human error.

Framing Wastes

The observed projects produced between 11.5 m^3 and 15.3 m^3 (15 and 20 cu yd). In three of the observed four homes, approximately 40% of dimensional-lumber wastes were from nonconsumables. Particle board (or pressboard) and plywood combined accounted for 20% of the framing wastes, and packaging materials were the remainder.

Table 4 presents a detailed breakdown of the framing wastes for project A. The quantities in parentheses represent that portion of waste that resulted from using a material as a consumable. For example, 15.6 m^3 of dimensional lumber was wasted on project A but only 8.6 m^3 originated as a consumable (e.g., lumber used for studs). The process of cutting stock-size lumber to fit was the main reason for lumber waste, contributing 7.8 m^3 or 90% of all consumable lumber waste. At least half of the lumber scraps were less than 61 cm (2 ft) long. Many of the longer scrap pieces were leftover pieces from lumber with large dimensions. These pieces are generally harder to reuse since they have very specific uses, such as floor joists.

Most dimensional-lumber waste is unavoidable since the majority results from process scrap due to the need to cut stock to the exact dimensions. This fact, however, does not necessarily mean that lumber waste has to end up as landfill (see Fig. 1). For example, scrap pieces of dimensional lumber offer many opportunities for reuse on or off the site. Despite the many uses of lumber waste, none of the observed framing crews had a consistent system for reusing their scrap. Most observed framers did not save leftovers in an organized fashion, nor did they search for pieces of scrap lumber that would meet a particular need. Instead, they generally obtained a new piece at the lumber stockpile and cut it to size. The amount of waste generated by this practice was difficult to assess quantitatively. Too many people were working and moving at one time, and some scrap pieces did get reused. However, in two of the four homes where framing was observed, the crews ran short of certain pieces of dimensional lumber. The direct causes of these shortages were not positively ascertained, but at least one builder felt that his framing crew had not made good use of their lumber.

A vehicle, running over a set of stock lumber, was responsible for an unusual 9% of the dimensional lumber waste for project C. In general, just as with brick and block, most lumber had suffered from some handling damage before it arrived on the site. Every bundle of banded dimensional-lumber that was inspected had corner pieces that had been somewhat "crushed" by the bands). In a few instances, as many as eight pieces of a bundle had sustained this type of damage. Such damages, however, rarely lead to land-

TABLE 4. Composition and Sources of Framing Waste for Project A

Composition of Waste			Sources of Waste (m^3)			
Waste type (1)	Quantity (m^3) (2)	Percentage (3)	Process waste (4)	Poor materials handling (5)	Human error (6)	Unknown (7)
Dimensional lumber	15.6 (8.6)	66	7.8	0.15	0.15	0.6
Pressedboard/plywood	4.0 (4.0)	17	3.9	0.76	0.0	0.0
Styrofoam	1.5 (1.5)	6	1.5	0.0	0.0	0.0
Cardboard boxes	2.5 (0.0)	11	Not available	Not available	Not available	Not available
Total	23.6 (14.1)	100	13.2	0.91	0.15	0.6

fills since subcontractors generally found other uses for those pieces of lumber. If the damage was serious or if the lumber was severely warped, the craftsmen would cut the piece into smaller segments for use as blocking and bracing or as nonconsumables.

Construction errors that lead to wasted lumber (always in the form of human error) were seen with some regularity. Most frequent mistakes included wall studs that were improperly cut or assembled and overhead door supports that had been made of the wrong-size lumber. Again, framers were often able to reuse the lumber with which they had erred. Many of these errors could have been avoided by reading the blueprints properly. For example, it was observed that the front stoop of the home had to be rebuilt because untreated lumber was used instead of treated lumber. The responsible crew stated that they had "always" used untreated lumber for stoops. The builder, however, pointed out that the blueprints had called for treated lumber. He felt that the crew (which worked short-handed at the time) had failed to read the blueprints.

In summary, framing produced an average of 13 m^3 (17 cu yd) of consumable material waste for the three observed projects. Overall, roughly 65% of that waste was dimensional lumber, and another 18–20% was plywood and pressboard. Surprisingly, 40% of all lumber wastes were nonconsumables (i.e., wallboards and temporary bracing), thus representing a high-priority area for waste reduction. On the other hand, process scrap accounted for 90% of the consumable material waste. Despite or may be because of this, no crew was observed as having a detailed material-use plan before they began framing. It seems that materials requirement plans, such as the one discussed by Leenders et al. (1989), could have a large impact on reducing dimensional-lumber wastes.

Drywall Wastes

"Drywalling" is a two-phase process. In the first phase, a crew will simply "hang" all the sheets necessary to cover all wall and ceiling areas. In the second phase, another crew will tape, float, skim, and sand the joints created where two Sheetrock panels meet. Traditionally, crews attempt to minimize joints by using as many whole sheets as possible. The argument for minimizing joints is that the fewer the joints, the less susceptible the wall will be to cracking as the building settles, doors are slammed, window frames expand and contract, and so on. However, the establishment of quality measures (e.g., number of cracks) or methods for the minimization of material and waste-disposal costs lay beyond the scope of this research project.

Only project A's drywall process could be observed during the available time. The two homes (A1 and A2) that made up project A produced 6 m^3 (8 cu yd) of Sheetrock wastes. Only dimensional lumber was a larger contributor to project A's waste stream with 15.6 m^3 (20.4 cu yd) of waste. Sheetrock predictably accounted for more than 95% of all drywall wastes, and packaging wastes accounted for the rest. While 90% of the Sheetrock waste accumulated as process scrap, 10% was caused by improper measurements. Generally, workers either incorrectly measured the size of the opening they needed to fill or cut the Sheetrock stock piece too short.

The drywall crew observed on this project worked speedily. The crew was usually broken down into two-man teams so that they could assist each other in difficult tasks such as installing ceilings or high walls. Often, one worker would call out a measurement, and the second worker would cut the Sheetrock. Short cuts were usually caused when one worker misunderstood the number the other had called—a simple example of a communication problem.

The necessity to cut stock material on site offers another opportunity to produce excess waste. Similar to framing, drywall crews were observed cutting a needed length of Sheetrock from a brand new sheet instead of using available scrap. There was no evidence that the builder for this project had done a detailed analysis of how much Sheetrock would be required to complete both homes, despite the fact that he had spent a long time estimating the dimensional lumber. His drywall materials estimate was based on previous experiences building this same home model. The drywall subcontractor, in turn, based his estimates on a rule of thumb of 100 sheets (sheets are 1.22 m by 3.66 m) per 92.9 m^2 (1,000 sq ft) of plan area. The builder disclosed that during negotiations for home A2 the subcontractor had offered to buy the materials (charging the builder for 136 sheets) and to pay for any material costs above his initial estimate. The builder had rejected the offer because he expected that only 107 sheets were needed. As it turned out, the home required 127 sheets.

As indicated, several factors have to be considered when minimizing the cost for drywall installation. Fig. 3 presents the generic relationships between the three basic cost components of drywalling.

The cost graphs for a low and a high waste-disposal fee show that the cost for the Sheetrock material and waste disposal cost are inversely proportional to jointing costs. Thus the minimal total cost is identified by a vertical tangent to a nonlinear curve indicated by point X. As can be seen, higher dumping cost will not only mean higher cost overall but also reduce

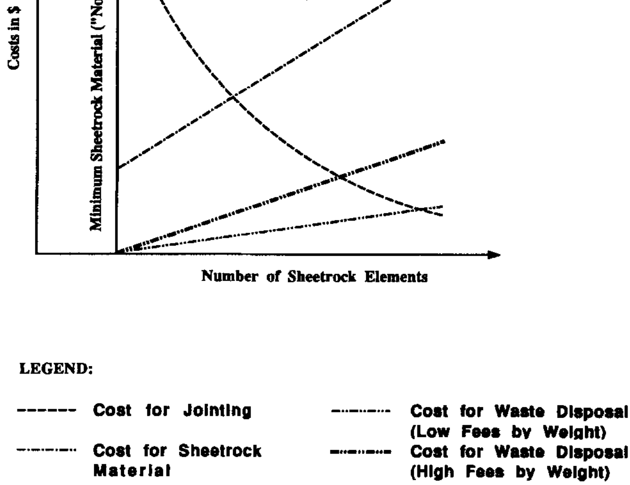

FIG. 3. Cost Components of Drywall Process

the optimal (minimal) amount of Sheetrock to be purchased (X'). Thus, higher disposal cost should cause a change in the traditionally "wasteful" drywalling operation. Of course, the presented cost overview does not include recycling of Sheetrock, as discussed by Kalin (1991). Naturally, this option would again change the optimum.

The data from two building construction sites support the fact that drywall waste, which consists of scrap Sheetrock, is a main contributor to the construction-waste stream. As with dimensional lumber, damage to drywall stock material during handling rarely resulted in waste, since chipped or cracked Sheetrock elements could still be used. It is felt that the low dumping fees for construction waste seem to be linked to the generally wasteful drywalling operation (Gavilan 1992). However, discussions with builders indicate that the traditional methods are being scrutinized in view of the increase in the local disposal fees.

SUMMARY AND CONCLUSIONS

It is accepted that waste reduction is the best and generally the most economical of the different waste-management options. Waste reduction, however, requires an understanding of the cause-and-effect relationships. This paper constitutes an initial attempt at testing a waste-stream framework for construction as a basic tool for the categorization and quantification of construction wastes. The framework was applied to several projects in residential construction. Field data indicate that most material wastes came from one of two sources: leftover from cutting stock material to fit and nonreusable nonconsumables. Defined as process waste, these two sources accounted for 80–85% of the brick and block wastes, 85–90% of dimensional lumber wastes, and 90% of Sheetrock wastes. The field observations revealed several opportunities for reducing the amount of generated waste. In particular, better and more detailed planning of materials and process requirements, as well as clearer communication between the builder and subcontractors, could significantly reduce construction waste.

The study also showed that improper materials handling caused 10–12% of brick and block wastes. Roughly the same percentage of lumber was damaged during handling, but hardly ever entered the waste stream. On-site handling of materials is generally not a problem, but some material arrives broken or is damaged too severely during unloading to be of any use. This is particularly true for brick and block, two relatively "brittle" materials. Plywood and dimensional lumber, both susceptible to weather damage, were inadequately protected during shipment as well as during on-site storage.

Wastes due to craftmen's error accounted for less than 5% of brick/block and dimensional-lumber wastes, and 10% of Sheetrock wastes. These wastes, like residual wastes, resulted mainly from poor communication either between crew members or between the contractor and the craftsman.

On three of the four observed sites, packaging wastes accounted for roughly 25–30% of all wastes. Thus, techniques to reduce packaging wastes merit further study.

Only indirectly related to the topic of solid waste in construction, the final conclusion supports the need for an integrated approach to waste-reduction efforts. The sources of waste seem to be closely linked to the traditional sources of low productivity. For example, hard-to-read plans result not only in ineffective work but also in more construction waste. Also, crews with poorly trained craftsmen have been observed to produce more

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waste. The writers are convinced that managing construction waste can also be viewed as an effort to achieve high construction productivity and safety. All these goals rely on detailed planning and the thoughtful use of material and human resources.

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