A Method to Measure Material-Use Efficiency in Construction Projects

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The construction industry is responsible for generating a high proportion of solid waste worldwide. Considering the increasing importance of sustainable development, reduction of material waste should be pursued more vigorously in the construction industry. An effective step for waste generation reduction is to increase the efficient use of materials. Material-use efficiency goes beyond waste generation, and aims at transforming waste to value again. This paper proposes a method that measures the sum of materials that was directly used in a structure plus the waste material that has been returned to the supplier, or recycled, divided by all the purchased materials for that project. By sorting and measuring wasted materials, this method provides a quantitative value for material-use efficiency, and is termed the Material Efficiency Index (MEI). The method facilitates keeping track of waste as well as detecting its root causes, thus preventing them. The Project Material Efficiency Index can be used as a performance measurement tool as well, in order to compare the efficiency of utilizing materials in different projects, a self-assessment tool by contractors to evaluate their crew performance, and, ultimately, a criterion to select more efficient contractors or subcontractors in subsequent projects.

Key words: material waste, lean, waste index, efficiency

Introduction

Regarding material consumption, there are two major concerns: one is sufficiency to meet the market demand and the other is the environmental effects of materials production and processing. In general, material demand is anticipated to double within 40 years. Huge increases in demand are accompanied by large environmental impacts. A key factor to control the material-demand increase is to control the waste of materials. (Allwood et al., 2011).

The construction industry is responsible for generating 35% of the world's solid waste (Hendriks et al., 2000). Considering huge costs of extraction, processing, production, and transportation of materials to construction sites, material waste imposes massive costs to the economy and damage to the environment. Taking measures to minimize waste of materials in construction can help mitigate effects to non-renewable resources, energy, air pollution, and, ultimately, global warming.

The existing literature regarding construction waste can be categorized in three groups. The first group of studies aims to measure the proportion of construction waste in total solid waste. The second group studies the sources of material waste generation in construction. The third group provides suggestions to minimize waste. These categories are reviewed in this paper.

The literature is limited regarding the efficient use of materials. 'Efficient use' goes beyond waste generation, and utilizes various types of instruments to decrease the demand of materials in construction. This paper presents a quantitative method to measure how efficiently materials are used in the construction process, based on implementing a waste management plan and taking measurements of waste on a weekly basis. This method calculates the efficiency based on the proportion of 1) cost of materials that was used in the structure, 2) the cost of material that was returned to the supplier and partially refunded, and 3) the cost of material that was sold as recycled material, divided by the cost of all purchased material. The output of the method is presented by a Material Efficiency Index (MEI) is used, with a number between 0 and 100, with ‘0’ representing the least efficient and ‘100’ representing the most efficient. Application of this method is expected to have the following advantages:

1. The method requires sorting of waste, which motivates recycling.

2. The amount of waste for each material is measured, which facilitates tracking the sources of waste and preventing them.
3. Material efficiency is measured by means of a quantitative value. Based on the scope of measurement, this value can be used as a performance measurement tool to evaluate crews, contractors, subcontractors, and the overall project team.

Background

Construction Material Waste Proportion in Total Solid Waste

Waste materials generated during construction and demolition (C & D) make up a large percentage of municipality waste. Apotheker (1990) reported that in the United States, C & D was responsible for 23% of total waste. Similarly, Hendriks et al. (2000) estimated the amount of C & D as 29% of the total waste in the U.S. Considering massive improvements of technology and other industrial successes, the rate of waste in the construction industry is alarming and is not showing a downward trend.

Causes of Construction Material Waste

In recent years, much research has been dedicated to the study of construction waste. Research performed in developed countries seemed to be more focused on the discipline of waste itself. In most studies, methods for data collection are surveys and case studies; mainly, the data processing is descriptive analysis (Yuan et al., 2012). In addition, much research has attempted to study the reasons for the high amount of construction waste. Based on the results of the research, the sources and causes can be categorized in six groups (see table 1). The body of research has recognized design issues as the main cause of construction waste. (Bossink et al., 1996; Faniran et al., 1998; Innes, 2004; Chandrakanthi et al., 2002; Ekanayake et al,, 2004; Wang et al., 2015)

Table 1

Sources and Causes of Material Waste in Construction

	Sources					
	Design	Procurement	Handling	Operation	Residual	Other
Causes	-Design errors -Design changes	-Over-ordering -Under ordering	- Damage in transportation -Poor storage	-Crew errors -Equipment malfunction	-Wrong cutting policy -Overmixing materials -Poor packaging	-Adverse weather -Accidents -Theft

Prevention of Construction Material Waste

Another category of research regarding construction waste includes studies on solutions to prevent the generation of waste. Five basic and common solutions suggested for this category are:

1. Developing the design such that the dimensions of building components match the available material sizes or standard sizes (Ekanayake et al., 2004; Baldwin et al., 2009; Wang et al., 2015)
2. Ordering materials such that the right material is obtained at the right time in the right location.
3. Handling the materials so that there is no harm during transportation or use.
4. Storing materials in such a way that weather, job site activities, etc., cannot damage them; storage keeps materials safe against theft as well.
5. Taking advantage of panelized or prefabricated construction, whenever possible (Nahmens et al., 2011).

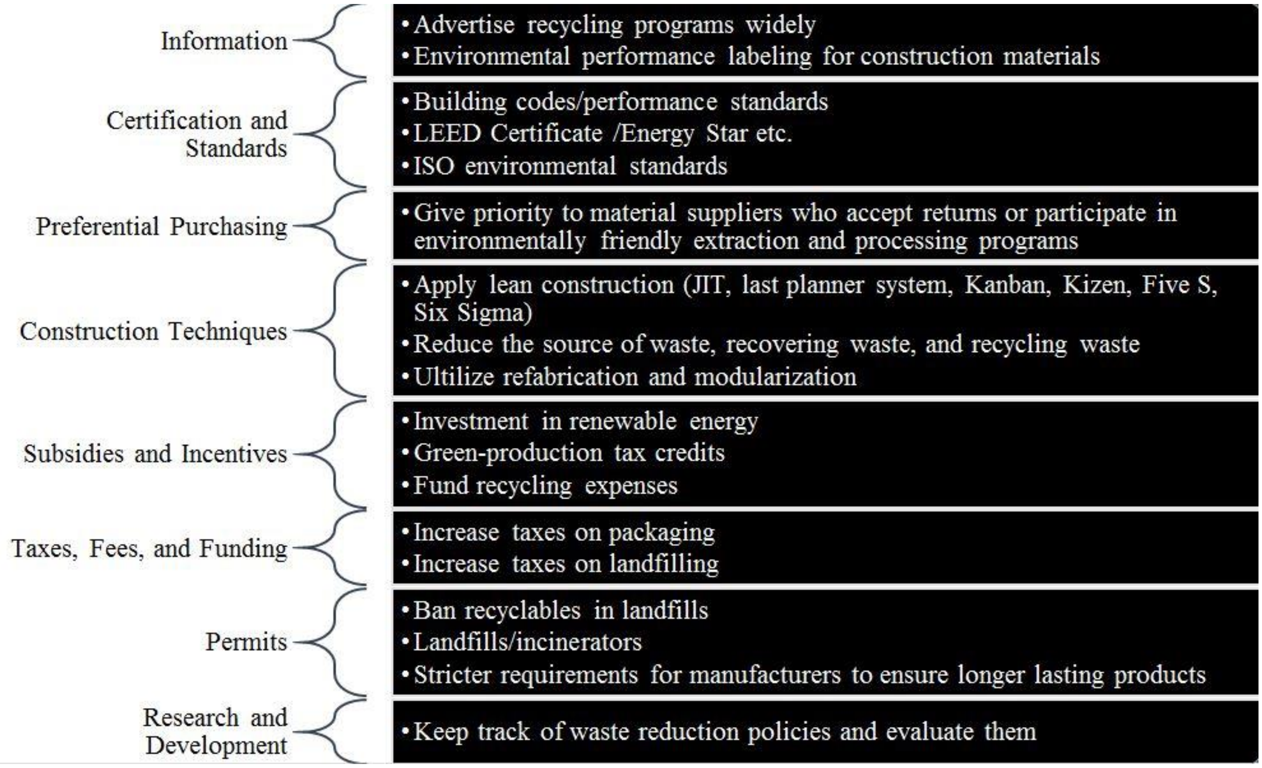
In addition to these policies, some researchers came up with more specific solutions about construction waste reduction. Baldwin et al. (2009) suggested fabricating building elements off-site in precast design as another solution. Yuan et al. (2012) suggested imposing higher fees for construction waste disposal and increase incentives for recycling. Wang et al. (2014) listed minimizing design modifications, using modular design and investment on waste reduction economic incentives as some other solutions for waste reduction during construction.

It should be noted that based on the waste hierarchy, source control of waste is the most efficient step regarding waste management. Reusing and recovering are the next solutions, followed by recycling. In addition, it is important to keep in mind that recycling construction waste is more difficult compared to recycling other wastes (Bossink et al., 1996) because of the presence of high levels of contamination and a large degree of heterogeneity (Brooks et al., 1994).

Construction Material Efficiency

Material efficiency means providing material services with less material production and processing (Allwood et al., 2011). This definition can be applied to construction materials as well. Based on this, material use is efficient if 1) the building design matches the dimensions of the material that are available in the market; 2) the materials are extracted, processed, ordered, transported, stored, and handled with generating the least amount of waste; 3) the residuals and packages are reduced, recovered, or recycled.

Research about material waste management has resulted in developing instruments that can increase the efficient use of materials (see figure 1). Studying and measuring all the aspects of material efficiency requires a life-cycle assessment of the material. In other words, all the materials that are used for a certain product should be tracked in various stages of extraction, processing, manufacturing, transportation, installing, and serving the end user. Once the material reaches its service life, it should be tracked to control how it is sorted, recovered, reused, recycled, and finally disposed.



Information	• Advertise recycling programs widely • Environmental performance labeling for construction materials
Certification and Standards	• Building codes/performance standards • LEED Certificate /Energy Star etc. • ISO environmental standards
Preferential Purchasing	• Give priority to material suppliers who accept returns or participate in environmentally friendly extraction and processing programs
Construction Techniques	• Apply lean construction (JIT, last planner system, Kanban, Kizen, Five S, Six Sigma) • Reduce the source of waste, recovering waste, and recycling waste • Ultilize refabrication and modularization
Subsidies and Incentives	• Investment in renewable energy • Green-production tax credits • Fund recycling expenses
Taxes, Fees, and Funding	• Increase taxes on packaging • Increase taxes on landfilling
Permits	• Ban recyclables in landfills • Landfills/incinerators • Stricter requirements for manufacturers to ensure longer lasting products
Research and Development	• Keep track of waste reduction policies and evaluate them

Figure 1: Instruments to improve material efficiency (Allwood et al., 2011 Table 5.1, with modifications).

The Material-Use Efficiency Index

The Merriam-Webster Dictionary defines efficiency as “effective operation as measured by a comparison of production with cost (as in energy, time, and money)”. It should be noted that for comprehensive assessment of material efficiency, a life cycle assessment is required. This assessment is not in the scope of this method proposed in this paper, which focuses on evaluating how efficiently materials are used during construction. It considers three types of materials as 'efficiently used' in the view of the owner:

1. Materials that have been directly used in the structure, with a coefficient of 1.0.
2. Materials that have been returned to the manufacturer for a partial return value, with a coefficient between 0 and 1, as the manufacturers normally deduct part of the original value when they accept returns.
3. Materials that have been sold to a recycling facility, with a coefficient between 0 and 1.

The method is presented in seven steps, as follows.

Step 1) Hiring a Waste Management Team

Based on the size of the project, a team is assigned to facilitate sorting the construction wastes as well as measuring them. The accuracy of the outputs of the method closely depends on how this team performs sorting and measurement. The construction manager decides how many people are required on the team. Every member of the Waste Management Team (WMT) should be a third party who is not involved in the construction process, and should be a representative of the owner in order to take care of the owner’s interests. Although adding a new team to the entire construction team imposes more costs to the owner, considering the fact that construction material commonly is estimated to be 45% of the total project cost, controlling the generation of waste and reducing it is a worthwhile investment. Furthermore, the WMT does not require a high level of skills, and laborers do not have to be highly paid.

Step 2) Waste Management Meeting

A meeting is held by the construction manager (CM), with obligatory participation of sub-contractors and supervisor(s). Project goals in reducing waste are defined collaboratively. For instance, the team can decide to achieve a Material Efficiency Index (MEI) of 95%. The WMT provides the required instructions, and presents the fundamental techniques to reduce waste generation.

Step 3) Waste Sorting

The laborers should be provided with instructions on how to sort and accumulate each type of wasted materials. Special measures should be taken with regard to hazardous wastes, for example, chemicals, including volatile organic compounds (VOCs), and electronics. Some wastes may be exempted due to safety or environmental issues. The amount of waste can be measured by volume or weight, but should be measured in a consistent manner throughout the project. The wastes can be transported from the job site at required intervals; however the weight or volume of the waste should be recorded before leaving the site. Instructions on how to sort the waste is not within the scope of this paper.

Step 4) Making Measurements

Before any waste leaves the job site, the WMT should fill out a table (see table 2). Measurements can be conducted on a weekly basis, with care taken not to miss any quantity. The 'returned' column records the amount of waste that is returned to the manufacturer. Some manufacturers accept their returned products for a specified percentage of the original value. If it is not possible to return any of the materials, this column can be eliminated. The 'recycled' column reflects the quantity of materials that had been sent to recycling facilities, and the 'disposed' column indicates the waste material that was carried to a landfill.

Table 2

Example of wasted material measurements

Material	Unit	Feb (1-7), 2015				Feb (8-14), 2015				Feb (15-21), 2015				Feb (22-28), 2015			
		Total quant.	Returned	Recycled	Disposed	Total quant.	Returned	Recycled	Disposed	Total quant.	Returned	Recycled	Disposed	Total quant.	Returned	Recycled	Disposed
Concrete and mixed rubble	lb																
Wood	Bf																
Drywall	Bf																
Asphalt roofing	lb																
Metal	lb																
Bricks	lb																
Plastic	lb																
Total																	

Step 5) Determining Coefficients for 'Return' and 'Recycle'

If recycled materials are sold, a coefficient determining their value should be defined for the products by the following equation:

$$Coef_{RECi} = \frac{Value_{RECi}}{Cost_{PERi}}$$

Where:

$Coef_{RECi}$ = Coefficient for determining the equivalent amount of material i which is recycled
$Value_{RECi}$ = Money that the recycling facility pays per unit of material i
$Cost_{PERi}$ = Purchace price of material i per unit

Assume that the recycling facility buys every pound of material i for \$12, and the purchase price of this material is \$100. The coefficient for recycled value of material i will be 12/100, or 0.12.

Similarly, another coefficient is determined for the value of returned materials by the following equation:

$$Coef_{RETi} = \frac{Value_{RETi}}{Cost_{PERi}}$$

Where:

$Coef_{RETi}$ = Coefficient for determining the equivalent amount of material i which is returned
$Value_{RETi}$ = Money that the material supplier pays per unit of material i
$Cost_{PERi}$ = Purchace price of material i per unit

It should be noted that if the owner is willing to recycle the waste with no money return, recycled materials still can be considered as 'efficiently used' by determining a coefficient that shows to what extent the owner considers the recycled material to be efficiently used.

Step 6) Determining the Material Use Efficiency Index for Each Material

This step introduces an index to evaluate how efficiently a material has been used on the job site. In other words, it tells us what percentage of the total material used on a project has been wasted. This formula is based on the simple logic of calculating productivity, which is expressed as:

$$Productivity = \frac{Outputs}{Inputs}$$

The outputs are the materials that have not been disposed to landfill. In other words, outputs are all the purchased materials minus the weight of wasted material plus the proportion of the amount of returned and recycled materials. All quantities need to be consistent in the measurement (weight or volume).

$$MEI_i = \left(\frac{(M_{PERi} - W_{TOTi}) + (M_{RECi} \times Coef_{RECi}) + (M_{RETi} \times Coef_{RETi})}{M_{PERi}}\right) \times 100$$

Where:

i = a numeric code given to each of the materials
MEI_i = Material efficiency index for material i
M_{PERi} = Purchased quantity of the total material i
W_{TOTi} = Total quantity of material i not used in structure (including disposed, returned and recycled)
M_{RECi} = Quantity of material i that has been recycled
M_{RETi} = Quantity of material i that has been returned

The above equation can be simplified:

$$MEI_i = \left(1 - \frac{W_{TOTi} - (M_{RECi} \times Coef_{RECi}) - (M_{RETi} \times Coef_{RETi})}{M_{PERi}}\right) \times 100$$

The advantage of knowing the efficiency of use for a specific material is that now the root causes of material waste can be detected because each material mainly is used by certain crews on the job site. For example, the crew who work with wood is the carpentry crew; therefore, if wood is being wasted at a higher rate than other materials, measures can be taken to control the waste with the carpentry crew.

The equation above was developed to define the material-use efficiency at the end of the project, and can assess the efficiency of the use of a certain material. However, it makes more sense if the measurement can help to avoid repeated mistakes and minimize the waste during the project and not at its end. Since measurements are conducted on a weekly basis, by some modifications in the equation, MEI_i can be determined at the end of each week. The difference in the equation is that instead of the total amount of purchased materials, the amount of purchased material that have been used during the target week (for which parameters have been measured) should be inserted into the equation. This is shown as:

$$MEI_{i,w} = \left(1 - \frac{M_{TOTi,w} - (M_{RECi,w} \times Coef_{RECi}) - (M_{RETi,w} \times Coef_{RETi})}{M_{PERi,w}}\right) \times 100$$

Where:

$MEI_{i,w}$ = Material efficiency index for material i during the week w (week of measurement)
$W_{TOTi,w}$ = Total quantity of material i not used in structure (including disposed, returned and recycled) during the week w (week of measurement)
$M_{RECi,w}$ = Quantity of material i that is recycled during the week w (week of measurement)
$M_{RETi,w}$ = Quantity of material i that is returned during the week w (week of measurement)
$M_{PERi,w}$ = Purchased quantity of material i that is used during the week w (week of measurement)

MEI is particularly useful to measure material-use efficiency in repeated activities. Based on this, the interval of the measurement can be set equal to duration of the activity. At the end of each activity, the material-use efficiency index shows the performance, and a progress diagram can be drawn to verify that the rate of waste is being reduced as the team detects the causes of waste generation and eliminates them.

Step 7) Determining the Material-Use Efficiency Index for Each Material

If the project manages to measure MEI for all materials of the material efficiency index for the entire project (MEI_P) also can be calculated. This can be used as evaluating criteria, which combines the performance of all crews to evaluate efficient use of materials in the entire project. To calculate MEI_P, simple averaging of all materials cannot be a good representative because the costs of materials differ. More expensive materials are expected to have a greater share in determining MEI_P. That is why a weighted average is used, based on the cost of each material. This is expressed as:

$$MEI_P = \sum_{i=1}^{n} \left(MEI_i \times \frac{Cost_i}{Cost_P} \right)$$

Where:

MEI_P = Material efficiency index for all materials in the entire project
$Cost_i$ = Total cost of material i
$Cost_P$ = Total cost of all measured materials in the entire project

Discussion

It should be noted that this method provides an approximation of material-use efficiency. This is because an accurate measurement of all wasted materials is not possible. Excluding this, the accuracy of the presented method merely depends on the quality of the measurements. Additionally, its preventive power in reducing waste depends on how the results are studied and followed up, and how the detected causes of waste are controlled. Regardless of the presented method’s ability to reduce generation of waste, since it requires close control of wasted materials, it is expected that such control can motivate laborers to increase their precautions in order to avoid waste generation. This can be considered as an indirect expected benefit of implementing this method.

This method has some requirements that closely overlap those that reduce the negative effects of building materials on environment. Although the goal of using the method is to reduce waste, thus reduce costs, it requires that the waste be sorted, which is the primary step in recycling materials. In addition, this method encourages returning any unused materials and recycling them. Currently many building projects – specifically, those that pursue LEED certification – implement waste management plans. Therefore, by adding a few more requirements to the current waste management plan, this method can be added to upgrade the quality of material waste reduction and reduce extraction of virgin materials if widely applied.

Areas for Further Research

The presented method is based on a simple logic that assumes that productivity is the outputs divided by inputs; this is widely accepted as a fundamental concept in the evaluation of productivity. Further research is needed to enhance the quality of the equations that were introduced in this paper. Additionally, measuring wasted materials during construction currently is not a common practice; therefore, applying different engineering techniques to control it is difficult. By filling the gap of insufficient numeric data regarding waste of material in construction, in future research, more evaluation methods and calculation techniques are expected to be applied.

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