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Quantifying the carbon footprint of lean waste

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QUANTIFYING THE

CARBON FOOTPRINT OF LEAN WASTE

by

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ABSTRACT

The objective of this paper is to provide a method of quantifying lean wastes in terms of carbon dioxide emissions by using value stream mapping. Lean manufacturing, a process based on waste identification and reduction, is a growing trend in industry and a proven method of lowering costs. The environmental impact of these wastes can be quantified by identifying the metrics associated with them, and using existing reports to convert those metrics into measurements of carbon dioxide. Growing environmental concerns are prompting federal government regulation of greenhouse gas or carbon dioxide emissions, as seen in the American Clean Energy and Security Act of 2009, passed by the House of Representatives and being considered in the Senate. This bill would have a significant economic impact on manufacturing businesses. And while many carbon footprint calculators are available for citizens to quantify their own emissions, there are currently none available for manufacturing companies to use in order to accurately quantify their carbon dioxide emissions to meet impending governmental regulations.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Katie Grantham, without whom this research would not be possible. I am especially grateful for her valuable advice and continuous support.

Thank you to my committee members, Dr. Scott Grasman and Dr. Elizabeth Cudney, for the time and effort they put forth. Additional thanks must go to Dr. Cudney for stepping in as my advisor while Dr. Grantham was on leave.

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1. Introduction

The objective of this paper is to establish a set of metrics to determine the carbon footprint of lean manufacturing processes. Already governments are beginning to impose restrictions that will limit the amount of greenhouse gas emissions in the coming years. A version of the American Clean Energy and Security Act, passed by the House of Representatives in June 2009, mandates a 17% cut in emissions by 2020 and upwards of an 80% cut by 2050, based on emissions from 2005 [1]. Since lean manufacturing has long been praised for its waste reduction, it is poised to capitalize on the "green waste" reduction, measurable in carbon emissions, while adding value. The companies who embrace lean manufacturing will be able to simultaneously embark on lean initiatives that increase their value while measuring and reducing their carbon footprint. This provides an objective quantification for both consumers and government regulators.

In this paper, carbon emissions calculations have been provided for several wastes that are commonly identified as part of a lean manufacturing value stream map. The carbon footprint can then be quantified for each state of the process. By subtracting the future state carbon emissions from the current state, the "greenness" of the lean manufacturing initiative can be quantified. This will benefit companies by assisting them to comply with impending government regulations, but also to provide concrete evidence of environmental friendliness to consumers.

2. Background

2.1. Emissions Regulation

As awareness and acceptance of climate change predictions grows, many consumers, citizens and governments are becoming increasingly concerned with environmental sustainability. In an effort to encourage energy efficiency, Congress is attempting to pass new laws that limit the amount of emissions companies can release.

This will be accomplished through a "cap and trade" system. Each company will be allowed a set amount of "carbon credits," which measure their allotted emissions. Companies who do not use all of these credits can sell them, thus providing financial incentive to reduce emissions [1]. In addition to U.S. Congressional action, United Nations climate change talks, including a recent event in Copenhagen will attempt to combat global warming through emissions caps. Such regulation is certain to have an economic impact on manufacturing companies. Part of the solution involves accurate calculations of current emissions, along with understanding how a basis in lean thinking can bring greener results.

2.2. Lean & Green

Since its development, lean manufacturing has focused on categorizing and eliminating non-value adding steps, or wastes. This structure lends itself directly to classifying and measuring a product of green waste: carbon dioxide emissions. The link between lean manufacturing and green manufacturing has been explored and found to be a significant effect on the process becoming green.

Many industrial engineers point to lean thinking as an indicator of green thinking [2]. Franchetti et al. define six goals of green engineering:

- Select low environmental impact materials
- Avoid toxic or hazardous materials
- Choose cleaner production processes
- Maximize energy and water efficiencies
- Design for waste minimization
- Design for recyclability and reuse of materials

The authors assert that these concepts can be implemented through lean manufacturing and go on to address the related aspects of lean based industrial engineering that can accomplish them. Among them are inventory control, which reduces space needed in a facility, thereby reducing heating, cooling, and energy costs; statistical analysis, including the lean tool of value stream maps; and logistics, an area in which waste can be cut through leaner transport and packaging of goods. Through this analysis, it is apparent that many lean tools exist that can contribute to achieving green engineering goals.

In addition to lean wastes, engineers have taken to calling out specific green wastes, which in similar fashion can be measured and systematically reduced. According to author Brett Wills, green wastes categories are: energy, water, materials, garbage, transportation, emissions, and biodiversity [3]. Metrics are specific to each waste; water is measured in gallons used, energy in kilowatt-hours, etc. In his approach, the traditional lean tool Value Stream Map is transformed into a Green Value Stream. He finds that through mapping the process and measuring green wastes through each step can allow reduction in the same way that lean wastes are decreased [3]. Although this method is beneficial in understanding where green wastes appear in the process, individualized metrics make it difficult to judge the overall green impact. Utilizing carbon dioxide emissions as the main metric accomplishes the dual tasks of clearly quantifying the "greenness" of the process and doing so while remaining consistent with metrics associated with emissions legislation.

2.3. Current Carbon Footprint Calculators

Carbon footprint calculators have become an important tool in increasing public awareness of how daily choices can effect greenhouse gas emissions. Time magazine lists the carbon footprint as one of The 50 Best Inventions of 2009 [4]. Anyone today can log onto the Internet and find a calculator that will estimate their individual or household carbon footprint. However, non-residential and accurate calculators are still lacking.

Eight online carbon footprint calculators were analyzed in an effort to benchmark current options. Five of these are intended for residential use while the remaining three are specific to businesses and organizations. Residential applications, such as the EPA Household Emissions Calculator, require user input regarding home energy use, travel information, and waste data [5]. This particular model also suggests and calculates scenarios to lower your emissions. The Global Footprint Network calculator does not allow for numeric input, but prompts users to answer on a scale of options [6]. Similarly, the Nature Conservancy uses only your zip code and type of home to estimate a starting footprint, then bases the remainder on questions that only allow for subjective answers [7]. Carbonify.com does use numeric input, but does not take into account as many categories as others [8]. CarbonFootprint.com, on the other hand, incorporates all necessary categories—heating options, transportation including public transit, and secondary emissions such as from food and waste, among others—and lets the user input figures directly from their utilities bill [9]. Despite some differences in techniques, all residential calculators displayed the final carbon footprint in terms of CO2, either in tons or pounds.

Non-residential calculators are more difficult to come by. The three analyzed all provide results in tons of carbon dioxide yet their level of detail can easily distinguish them from each other. CarbonMe.org focuses almost solely on transportation, specifically employee commutes and air travel [10]. Climate Trust included infrastructure, transportation, and shipping in its calculations—more comprehensive but still not sufficient to fully quantify a manufacturing process [11]. The Seattle Climate Partnership incorporates energy, transport, materials, and waste data into its calculator. Exact data is encouraged, but estimates can also be used if necessary. Unfortunately, this calculator is designed specifically for the Seattle area, with energy information especially for that region [12].

From this analysis it is evident that a carbon footprint calculator must be specially designed for a lean manufacturing process. Current methods will be used as reference, but they must be expanded on in order to adequately quantify the many steps of a manufacturing process.

3. Methodology

The approach to quantify carbon dioxide emissions begins with lean wastes. For the purposes of this paper, these have been identified as the Toyota Seven Wastes: transport, inventory, over production, motion, over processing, defects, and waiting [13]. Carbon dioxide emissions for these lean wastes were established by first breaking each down into components that can be more easily measured. The fist step in this process is shown in **Table 3.1** below. These components were then divided into specific measureable wastes that used unit conversions to determine the appropriate calculations to quantify carbon dioxide emissions. The unit conversions were determined by first identifying standard metrics to measure the wastes and utilizing carbon coefficient data from the U.S. Environmental Protection Agency to convert those metrics into measurements of carbon dioxide.

Table 3.1. Lean Waste to General Green Waste

Lean Waste	General Green Waste
Over Production	Storage
	Production time
	Scrap
Inventory	Storage
	Raw material scrap
Transport	Shipping
	Packaging scrap
Defects	Scrap
	Production time
	Inspection time
Motion	Time
	Scrap
Over Processing	Production time
Waiting	Time

General categories of green waste were interpreted directly from lean wastes. From this starting point it was possible to retain a certain traceability between lean and green wastes. Translating lean waste into its carbon dioxide emitting components involves evaluating its environmental effects and decomposing each category into manageable parts. These general green waste categories include time, storage, shipping and scrap, and their breakdown can be seen in Table 2. Storage is an outcome of excess inventory, which requires additional space with lighting, heating, and cooling. Time refers both to production time, including the energy used in the production process, and to additional time the building must be lit, heated, and cooled. Scrap takes into account the material waste of a process. These green related outcomes can all be easily measured, and converted to carbon dioxide emissions in a few steps.

Table 3.3. Measuring Green Wastes

General Green Waste		**Measurable Outcome**	**Metric**
Storage	Heating/cooling	energy	kWh
	Lighting	electricity	kWh
Time	Heating/cooling	energy	kWh
	Lighting	electricity	kWh
	Equipment	energy	kWh
Shipping	Fuel	efficiency	gallons/mile
Scrap	Disposal	material waste	lbs

The Solid Waste Management and Greenhouse Gases report by the EPA provides carbon coefficients of fuels used in heating, transportation, and electricity generation, as well as carbon footprints of 21 common single-material wastes [14]. Using the carbon coefficients of fuels provided in this report, units were converted to match the metrics determined in an earlier step. This process and its results are shown in Table 3.

Table 3.4. CO2 Emissions of Fuels

Fuel Type	kg CE per million Btu	kg CO2 per million Btu	lb CO2 per million Btu	lb CO2 per kWh
Gasoline	19.15	70.93	156.36	0.53
Diesel	19.75	73.15	161.26	0.55
National Avg fuel mix for electricity	15.83	58.63	129.26	0.44
Natural Gas	14.33	53.07	117.01	0.40

This report investigated the amounts of various types of energy used in the production and transportation of each of these wastes, along with non-energy emissions from the process. One material analyzed was aluminum—specifically aluminum cans. Based on the current mix of 51% recycled inputs, 2.24 metric tons of carbon equivalent (MTCE) are produced for every ton of aluminum cans [14]. Carbon equivalents are used as the metric in this report to account for differences in effects of greenhouse gases. A simple conversion can put this in terms of carbon dioxide. Since CO2 is 12/44 carbon by weight, it can be calculated that every ton of aluminum cans produced has a carbon footprint equal to 8.30 tons of carbon dioxide. This report also includes data on waste management methods, which can later be used to include the effects of recycling or using landfills on the carbon footprint of a lean manufacturing process.

4. Green Waste Quantification Example

The example in this section demonstrates the carbon dioxide emission quantification for the Transport waste. In lean thinking, transport is non-value adding due to monetary costs related to shipping and packaging [13]. The carbon dioxide emissions related to transportation, however, involve fuel and packaging material. Therefore a link must be determined to enable the environmental value quantification of the transport waste.

In order to illustrate the connection between lean and green, take a fictional St. Louis company, Redbird, Inc., whose process used overnight delivery to meet its shipping deadlines to its customer in Boston. Using lean thinking, Redbird Inc. designed a new layout that reduced motion and eliminated several over processing wastes. This shortened processing time, allowing for ground shipping. The company also determined that smaller boxes can be used, amounting to 20% lower cardboard usage.

According to The Climate Trust, the carbon footprint of air shipping is 0.0009 ton CO2 per ton-mile, while that of ground shipping is 0.00033 ton CO2 per ton-mile [15]. Air distance from St. Louis to Boston is 1,308 miles, and ground distance is 1,179 [16,17]. That amounts to 1.1772 ton CO2 per ton of air shipped product, and 0.3891 ton CO2 per ton of ground shipped product—a 67% decrease in CO2.

After considering fuel, packaging can be analyzed. The carbon equivalent for corrugated cardboard (35% recycled) is 0.24 tons per ton of product [14]. Therefore its footprint is 0.89 tons CO2 per ton of corrugated cardboard. Ultimately, lean manufacturers will be able to input their own figures into a spreadsheet to easily utilize these calculations.

5. Conclusions and Future Work

Given the impending legislation on emissions regulation, it is more important than ever for companies to reduce their environmental impact. A step has been made toward carbon measurement using lean waste principles. Lean manufacturing technology can serve as a mechanism to make companies compliant with impending legislation. There is still work to be done in translating lean wastes into green wastes. Future work will include completing a comprehensive list of emissions sources, computing their carbon impact, and organizing them into a calculation.

PAPER

6. Introduction & Motivation

The objective of this paper is to provide a method of quantifying lean wastes in terms of carbon dioxide emissions through the use of value stream mapping. At the urging of concerned environmental scientists, citizens, and consumers, governments are beginning to impose restrictions designed to limit the amount of greenhouse gas emissions in the coming years. A version of the American Clean Energy and Security Act, passed by the House of Representatives in June 2009, mandates a 17% cut in emissions by 2020 and upwards of an 80% cut by 2050, based on emissions from 2005 [Sheppard, 2009].

Since lean manufacturing has long been praised for its waste reduction, it is poised to capitalize on the related "green waste" reduction as has been highlighted by the United States Environmental Protection Agency and authors such as Brett Wills [Wills, 2009; EPA, 2006; EPA, 2007]. This paper will show connections between wastes of the lean and green worlds and demonstrate how to identify and quantify the green waste inherent in the process in the style of carbon footprint calculators while still adding value to the process. The companies who embrace lean manufacturing will be able to simultaneously embark on lean initiatives that increase their value while measuring and reducing their carbon footprint. This provides an objective green quantification for the company, environmentally conscious consumers, and forms a basis for future government regulations.

In this paper, carbon emissions calculations have been provided in a table of unit conversions for a variety of measurable outcomes of lean wastes. These outcomes were identified by analyzing each lean waste in terms of its outcomes and their connections to green wastes. By incorporating select green measurements into the common lean practice of value stream mapping, companies can easily record their data, combine it with unit conversions, and monitor their CO_2 emissions.

7. Literature Review

7.1. Emissions Regulations

As awareness and acceptance of climate change predictions grows, many consumers, citizens, and governments are becoming increasingly concerned with environmental sustainability. The Intergovernmental Panel on Climate Change (IPCC), a scientific body established by the United Nations Environmental Programme and the World Meteorological Organization, "reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change [30]." Their 2007 report states:

> *Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years [...] The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture. [...]*
>
> *Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.* [31]

In an effort to encourage emission reduction by increasing energy efficiency in the United States, Congress is attempting to pass new laws that limit the amount of emissions companies can release through policies including a "cap and trade" system. In this system, each company will be allowed a set amount of "carbon credits," which measure their allotted emissions. Companies who do not use all of these credits can sell them, thus providing financial incentive to reduce emissions [1]. In addition to U.S. Congressional action, United Nations climate change talks continue their aim to combat global warming on an international level through emissions caps. Such regulation is certain to have an economic impact on manufacturing companies. Part of the solution involves accurate calculations of current emissions, along with understanding how a basis in lean thinking can bring greener results.

7.2. Lean & Green

Since its development, lean manufacturing has focused on categorizing and eliminating non-value adding steps, or wastes [25]. This structure lends itself directly to classifying and measuring a product of green waste: carbon dioxide emissions. The link between lean manufacturing and green manufacturing has been explored and found to be a significant effect on the manufacturing process becoming green [22, 26].

According to the U.S. Environmental Protection Agency (EPA), "Lean is a business model and collection of methods that help eliminate waste while delivering quality products on time and at least cost [22]." The development of Lean thinking and its roots in the automotive industry has been studied and documented by James P. Womack, Daniel Roos, and Daniel P. Jones in *The Machine that Changed the World*, and later refined by Womack and Jones in *Lean Thinking* [23, 24]. They have distilled lean thinking into five principles that operate as shown in Figure 7.1 [25].

Many industrial experts point to the prevalence of lean thinking and its ties to green thinking as a method of becoming more green [2, 3, 25]. An *Industry Week* article states that the 2007 IndustryWeek/MPI Census of Manufactures found that 70% of companies are implementing some form of lean, and goes on to outline how companies such as General Electric and Canyon Creek Cabinet Company have found success combining lean and green initiatives, simultaneously demonstrating the popularity of lean and its potential for producing green benefits [25].

In an *Industrial Engineer* article, Franchetti et al. define six goals of green engineering:

- Select low environmental impact materials
- Avoid toxic or hazardous materials
- Choose cleaner production processes
- Maximize energy and water efficiencies
- Design for waste minimization
- Design for recyclability and reuse of materials

The authors assert that these concepts can be implemented through lean manufacturing and go on to address the related aspects of lean based industrial engineering that can accomplish them [2]. Among them are inventory control, which reduces space needed in a facility, thereby reducing heating, cooling, and energy costs; statistical analysis, including the lean tool of value stream maps; and logistics, an area in which waste can be cut through leaner transport and packaging of goods. Through this analysis, it is apparent that many lean tools exist that can contribute to achieving green engineering goals. What is needed is a framework that can tie lean thinking to quantifiable green outcomes.

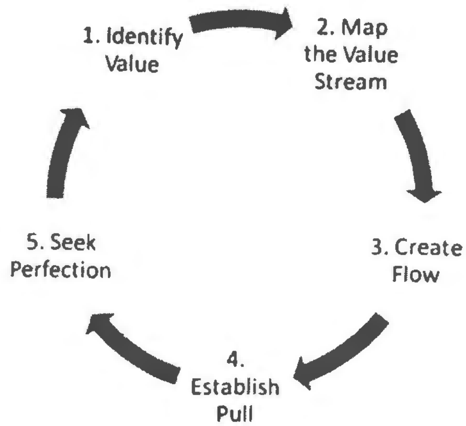

Figure 7.1. Five Principles of Lean

7.3. Lean Value Stream Mapping

The practice of value stream mapping is an important component of lean manufacturing that allows companies to map material and information flows of an entire process in order to identify wastes [18]. Value stream maps (VSMs) represent either the current state (the present process) or the future state (the process goal). In both states the VSM diagrams the suppliers, consumers, production control, and the inventory and information flows between them. Each value stream activity has a process box in which metrics such as changeover times are written. In *Learning to See*, Rother and Shook emphasize the importance of physically walking through the process to measure and record data of the current state [18].

When all relevant details are collected, the current state value stream map can be analyzed for lean waste. Improvements to the process are found and documented in a future state map, which represents the process goal. Modifications are made to meet this goal, and the value stream mapping method is periodically repeated to further decrease waste.

As an existing and well-established recording tool, value stream mapping is in a prime position to aid in tracking green wastes. By incorporating select additional data, this traditional lean tool can be utilized in new ways. The EPA has addressed this in some of their lean publications [19, 20]. *The Lean and Environment Toolkit* suggests weighing the amount of scrap generated in each step of a process, as seen in Figure 7.2.

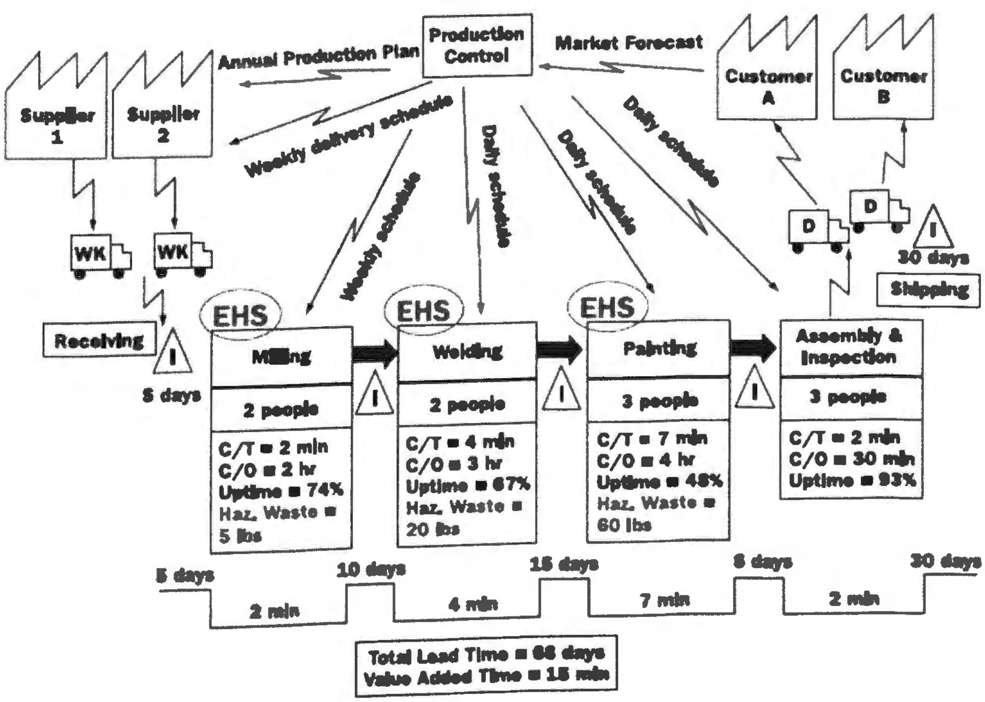

Figure 7.2. Current State VSM with Environmental Data

7.4. Green Wastes and Green Stream Mapping

In addition to lean wastes, some have taken to calling out specific green wastes, which in similar fashion can be measured and systematically reduced. According to author Brett Wills, green waste categories are: energy, water, materials, garbage, transportation, emissions, and biodiversity [3]. Metrics are specific to each waste; water is measured in gallons used, energy in kilowatt-hours, etc. In his approach, the traditional lean tool Value Stream Map is reinvented as a Green Stream Map. Wills argues that mapping the process and measuring green wastes through each step can allow reduction in the same way that lean wastes are decreased [3].

7.4.1 Wills' Green Wastes

Wills thoroughly explains each of his green wastes, highlighting both monetary and environmental effects. Energy "specifically refers to energy and fuels (such as natural gas) used to power electrical and mechanical devices." It is considered to be waste when overused, if it comes from a 'dirty' source, or when bought from an outside source [3]. Water is a green concern because of the finite supply of fresh water. The overuse of water is a waste, in financial terms for the expense of consuming fresh and disposing of contaminated water, and in depletion of it as a resource [3]. "Material waste comes from a global design flaw—designing virgin raw materials into products that are designed to end up in a landfill [3]." Wills argues that companies should design for reuse, using a "cradle to cradle" concept. Garbage is an obvious green waste, and includes anything that is thrown away. Landfill, recycling, and incineration all produce greenhouse gas emissions. Transportation includes transport of people, materials, supplies, and finished products. Emissions captures those directly "created at your location, such as inside that oven by baking or cooking items containing volatile organic compounds (VOCs) or other toxins that are then exhausted into the atmosphere." Biodiversity waste is created when a disruption is caused in the environment – such as removing trees when building a new factory or through a continuous activity like storing garbage or overharvesting.

This comprehensive list of green wastes address environmental concerns including climate change, natural resource sustainability, and wildlife preservation. Unfortunately, such a broad focus could prove costly for many companies.

7.4.2 Green Stream Mapping

The procedure for creating a Green Stream Map closely resembles that for a Value Stream Map; the initial structure of diagramming suppliers, customers, value stream activities and information flow is identical. However, it focuses solely on green waste in each step and is not intended as a tool to make the process more lean. For example, process boxes contain only green waste data and inventory flow is not modeled. Also, the production control diagram is reinterpreted as "Admin & Support," often referred to as the "overall building," and encompasses building activities external to the manufacturing process. If a green waste is identified in a value stream activity, or in the overall building section, its symbol is recorded in the process box.

The true waste measurement and elimination phase then begins through completion of waste-specific worksheets provided by Wills. A series of steps for each waste outline the systematic identification, measurement, and elimination of each through the value stream and throughout the entire building. For example, the steps for eliminating material waste are shown in Table 7.1. These steps are recorded in the worksheets provided, including the current state worksheet as seen in Table 7.2. Steps 1 - 4 refer to the current state Green Stream Map, while Step 5 is part of the future state.

Table 7.1. Wills' Material Waste Elimination Steps

Material
Step 1: Identify the input and output of materials in each activity of your value stream as well as in the overall building.
Step 2: Measure the recycled/recyclable and compostable content of each material input and output.
Step 3: Classify each material input and output as a biological nutrient, and technical nutrient, or neither.
Step 4: Assess materials according to their impact on environment and society.
Step 5: Phase out materials with negative environmental impact.

Table 7.2. Wills' Material Waste Elimination Worksheet

Material Waste Elimination Worksheet								
Activity or Area:	Value Stream Activity 1: Stamping							
Current State								
Identify		Measure						
Input		Output	Material Makeup		Classify			Assess
Item & Qty	Material Makeup	Item	Input	Output	Tn	Bn	LF	
Steel coil (2 per day)	100% cold rolled	frame	25% recycled	100% recyclable	X			yellow

The method of identifying and measuring material waste is highly detailed, requiring information on material makeup (ideally to the level of 100 ppm) and classification as technical or biological nutrients. Step 4 calls for assessment of the environmental and societal impact of materials, which Wills describes as follows:

> *Finding out what impact the material is having on the environment and human health can be approached in a few different ways. Research the Web by searching for "environmental impact or human health impact of [material x]" or "effect of [material x] on fish life." Approach local environmental organizations, nongovernmental organizations (NGOs), and government organizations to ask for help. The information is out there and, with a little effort, you can find it. Once you know the environmental impact a material can have on the environment, you then want to follow the cradle-to-cradle process of rating it using a color code[.]*

The color-coded ratings are defined in Table 7.3. This means of identifying and measuring material waste is repeated for each value stream activity and for the entire building. Each of the other six wastes has its own steps and worksheets. Ultimately, data from the worksheets is transferred to the Green Stream Map, as in Figure 7.5. Additional worksheets are used to reduce green wastes and achieve the future state (step 5, in this case).

Table 7.3. Wells' Material Waste Ratings

Category	Description
Green	Little or no risk to environment or human health from using this substance.
Yellow	Low to moderate risk associated with using this material. Unless you can substitute this material with one that is rated green, it is acceptable for use.
Red	High impact and risk to the environment and human health from using this material. A strategy for phasing out this material and replacing it with a green or yellow material needs to be developed.
Gray	Risk data is missing or incomplete. Further investigation and research is needed in order to rate the material.

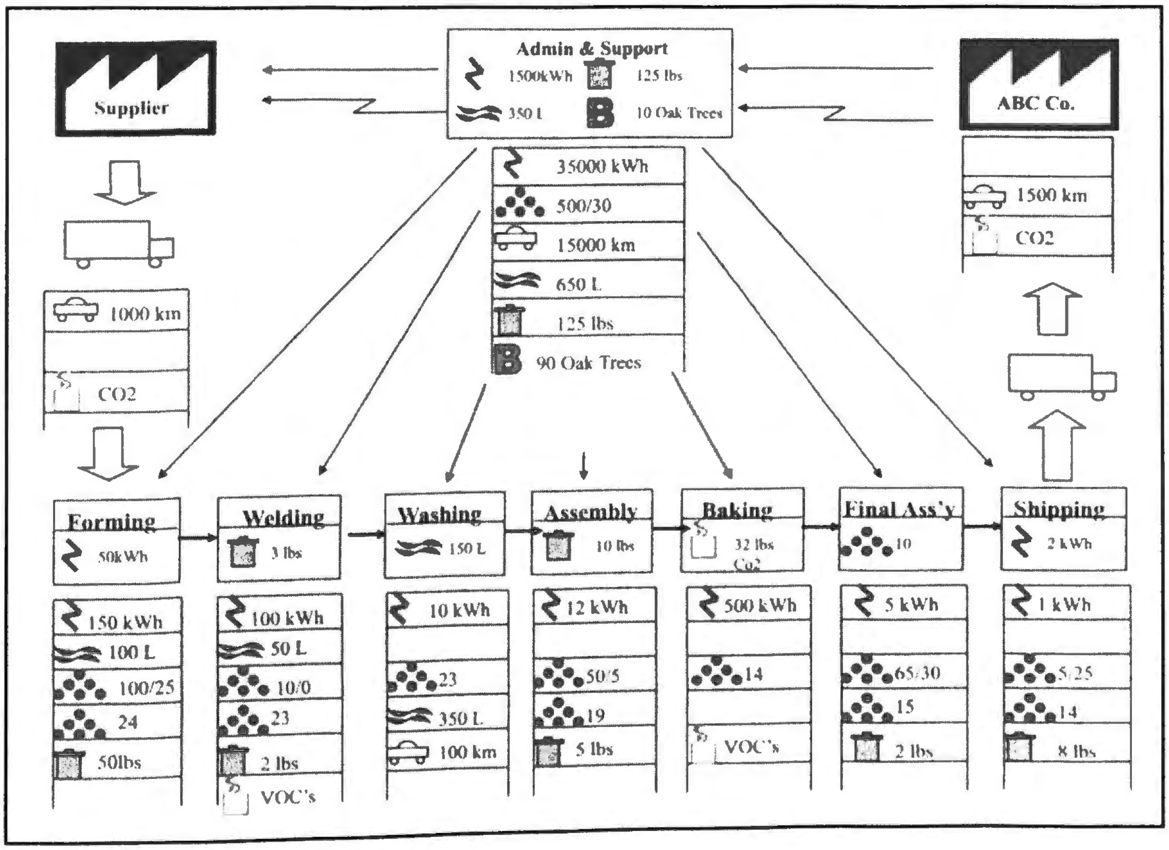

Figure 7.5. Wills' Current State Green Stream Map

Although this method is beneficial in understanding where green wastes appear in the process, individualized metrics make it difficult to judge the overall green impact, as well as the relative effects of each green waste. Some of Wills' ratings, such as the color-coded assessment of materials, are also highly subjective. Utilizing carbon dioxide emissions as the standard metric accomplishes the task of clearly and objectively quantifying the "greenness" of each part of the process and doing so while remaining consistent with metrics associated with emissions legislation.

Wills' method also requires major time and personnel commitments from the manufacturing company. In addition to the time consuming research required just to calculate material waste, Wills' suggestions include hiring a professional energy auditor for an energy assessment and consulting environmental firms to determine the amount of trees and wildlife that were affected by the construction of the company's facilities. His commitment to the environment is respectable, and some companies who are equally committed will no doubt find his method to be right for them.

Yet despite his use of lean tools, Wills does not address the reduction of lean waste that has been a verified technique of adding value. For those companies that want – or are required – to reduce their carbon footprint but are concerned by cost, using the proven practice of lean thinking combined with green measurements and conversion factors to calculate emissions can be a low effort alternative.

7.5. Current Carbon Footprint Calculators

Carbon footprint calculators have become an important tool in increasing public awareness of how daily choices can effect greenhouse gas emissions. Time magazine lists the carbon footprint as one of The 50 Best Inventions of 2009 [4]. Anyone today can log onto the Internet and find a calculator that will estimate their individual or household carbon footprint. However, non-residential and accurate calculators are still lacking.

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From this analysis it is evident that a carbon footprint calculator must be specially designed for a lean manufacturing process. Current methods will be used as reference, but they must be expanded on in order to adequately quantify the many steps of a manufacturing process.

8. Methodology

8.1. Linking Lean Wastes and Green Wastes

This approach to quantify carbon dioxide emissions of a process begins with lean wastes. The concept of waste is integral to lean thinking—in order to add value, waste must be reduced, with the ultimate goal of being completely eliminated. For the purposes of this paper, lean wastes have been identified as the Toyota Seven Wastes: transport, inventory, over production, motion, over processing, defects, and waiting [13]. Some, including author Brett Wills, propose a combination of "lean and green" that adds "green" as the eighth lean waste category [3]. Alternatively, this approach treats green waste as an outcome of each of the Toyota Wastes. Recognizing green waste as a product of leans wastes, much as overspending is seen as a product of lean wastes, underscores the complex yet overlapping relationships between lean and green.

8.1.1 Analyzing Lean Wastes

With the intent of calculating a carbon footprint in mind, early work in this approach began by breaking lean wastes into manageable outcomes that result in greenhouse gas (GHG) emissions. These heat-trapping GHG emissions stem from natural and human created sources such as burning fossil fuels for electricity, transportation, or production of resources. While additional factors influence environmental sustainability in terms of plant and wildlife health, for example, this approach focuses on the quantifiable GHG emissions that governmental regulations address.

Each lean waste was analyzed for green outcomes that ultimately result in GHG emissions. For instance, over production describes the waste resulting from producing too much of a product or producing it too soon; this leads to the cost-inducing lean outcome of selling the product at a reduced price, if at all, and increasing the on site inventory, which adds no value. This also leads to the green outcomes of excess production time, which requires more energy for machine operation; additional storage, and therefore space that needs to be lit, heated, or cooled; and scrap in the form of material waste to be recycled, incinerated, or deposited in a landfill.

Similarly, inventory can be traced to storage and scrap, in this case also including raw materials or chemicals that may have a shelf life and could require more environmentally wasteful forms of disposal. Transport of goods and materials is costly, and the obvious green outcome can be described as "shipping" and accounts for the fuel burned. Also, production of the packaging used in transport produces emissions, and is designated as "packaging scrap." Defects bring about material scrap and cause excess production time to re-work parts. The most significant green outcome of motion, waiting, and over processing is time; in the case of motion and waiting this refers to the time the building is lit, heated, or cooled, and in the case of over processing it also includes machine use.

Through this analysis green outcomes were listed for each waste, as summarized in Table 8.1, and then consolidated into the four major categories of time, storage, shipping and scrap, shown and further described in Table 8.3. Storage is an outcome of excess inventory, which requires additional space with energy-using lighting, heating, and cooling needs. Time refers both to production time, including the energy used in the production process, and to additional time the building must be lit, heated, and cooled. Scrap takes into account the material waste of a process, including emissions from production of that material as well as emissions from its recycling or disposal. Shipping addresses the fuel burned in transportation of goods and products to and from the site.

Table 8.3 summarizes these results and also specifies measurements associated with each. These metrics refer to units companies can readily use to track these categories and calculate their carbon footprint. These green outcome categories serve as the first step from lean wastes to their associated carbon emissions. They, in turn, are translated into categories of green waste, as seen in the next section.

Table 8.1. Green Outcomes of Lean Wastes

Toyota Seven Wastes	Lean Description	Green Outcome
Over Production	A product that cannot be sold, or is sold at a reduced price, producing a product before the customer needs it	storage, excess production time, scrap
Inventory	Excess inventory must be stored, ties up cash	storage, raw material scrap (shelf life)
Transport	Unnecessary movement is wasteful, potential damage to product	travel, packaging scrap
Defects	Re-work is costly, as is sorting and inspecting, and recycling	scrap, excess production time
Motion	Excess operator motion can cause injury and incur costs	time
Over Processing	Extra processing does not always add value to product	excess production time
Waiting	Operators should not wait on machines	time

Table 8.3. Green Outcome Results and Measurements

Green Outcome	Result	Measurable Outcome	Metric
storage	more space needed	energy used for heating/cooling/lighting space	kWh
time	more shifts, equipment runs longer	energy used for heating/cooling/lighting and running equipment	kWh
travel	vehicles	fuel, efficiencies	gallons/mile
scrap	material production, recycling, disposal	energy used to recycle or dispose	lbs, cubic ft

8.1.2 Translation to Green Waste

Green outcome categories are an important first step in describing the connections between lean wastes and the carbon footprint of a process. Their primary purpose is to serve as a link between lean wastes and the green waste inherent in each of those lean wastes. Due to some overlap in their associated metrics and in order to provide more clear categories, it makes sense to translate these green outcomes into a set of defined green wastes. Author Brett Wills' green wastes—energy, water, material, garbage, transportation, emissions, and biodiversity—were found to represent a comprehensive overview of environmental sustainability metrics.

However, not all of these green wastes are relevant in quantifying a carbon footprint based solely on emissions. Green wastes were examined for their relevance to greenhouse gas emissions. Energy use almost always depends on processes, such as burning coal or natural gas, that produce GHG emissions. Likewise, transportation relies primarily on burning fuels, which results in carbon emissions. Material and garbage can be measured in terms of their carbon emissions associated with original material production and their type of disposal or recycling.

On the other hand, water and biodiversity measure factors that affect the environment, but not in terms of carbon emissions. And while the emissions category of green waste would appear to be significant, most emissions produced on-site, such as volatile organic compounds, have negligible global warming implications.

Results from this analysis and links between the Seven Toyota Wastes and Wills' green wastes were analyzed and the relations are found in Table 8.5 and Table 8.7. Storage and time are traced to energy – the electricity or fuel used in the facility. Shipping is defined by the green waste of transportation, which measures fuel use of methods of transport. Scrap is divided into material and garbage wastes, which are both categories of physical components but are distinguished by where they are disposed. Garbage is disposed of by the company, whereas material is sent off site as part of the product or its packaging.

Translating lean wastes to green wastes shows how these environmental factors are in fact part of the original lean wastes and not an unrelated outcome. In addition to showing this relevance, defined green wastes are helpful in practice to identify what to look for and which measurements to record during the data collection stage of value stream mapping. While green wastes are allocated to lean wastes in this analysis in order to show their connections, it is not necessarily important to directly trace CO_2 back to lean wastes in the measurement stage of this method.

Table 8.5. Translating Green Outcomes to Green Wastes

Green Outcome	Green Waste
Storage	Energy
Time	Energy
Shipping	Transportation
Scrap	Material
	Garbage

Table 8.7. Relations of Lean and Green Wastes

Lean Waste	Green Waste
Transport	Transportation
	Material
Defects	Garbage
	Energy
Over Production	Energy
Inventory	Energy
Motion	Garbage
Over Processing	Energy
Waiting	Energy

8.2. Conversion Factors

In this research, greenhouse gas emissions are measured in units of carbon dioxide equivalent (CO2E). Greenhouse gasses are compared in terms of their global warming potential (GWP), or how much heat they are capable of trapping, in relation to other gasses. Carbon dioxide is the reference gas; 1 kilogram of CO_2 has a GWP of 1 while, for example, the same amount of CH_4 has a GWP of 21 [14]. Source data gathered from the EPA primarily uses carbon equivalent (CE), which is easily converted back to CO2E in order to retain consistency with current carbon footprint calculators.

Transportation fuel emissions conversion factors were found at carbonfund.org, part of a list of factors used in the carbon footprint calculator on the same site [21]. These were listed in pounds CO2 per ton-mile, and did not need to be converted.

The Solid Waste Management and Greenhouse Gases report by the EPA provides carbon coefficients of fuels used in heating, transportation, and electricity generation, as well as carbon equivalent footprints of twenty-one common single-material wastes [14]. Using the carbon coefficients of fuels provided in this report, units were converted to better reflect the metrics used in typical companies. For example, in **Table** 8.9 emissions from energy usage were converted from kilograms CE per million Btu to pounds CO2E per kilowatt-hour. This will allow users to work with familiar units on a scale appropriate to their needs.

Table 8.9. Energy Emissions Conversion Factors

Fuel Type	kg CE per million Btu	kg CO2E per million Btu	lb CO2E per million Btu	lb CO2E per kWh
Gasoline	19.15	70.93	156.36	0.53
Diesel	19.75	73.15	161.26	0.55
National Average fuel mix for electricity	15.83	58.63	129.26	0.44
Natural Gas	14.33	53.07	117.01	0.40

This EPA report investigated the amounts of various types of energy used in the production and transportation of each of these wastes, along with non-energy emissions from the process. One material analyzed was aluminum—specifically aluminum cans. Based on the current average of 51% recycled inputs, 2.24 metric tons of carbon equivalent (MTCE) are produced for every short ton of aluminum cans [14]. A simple conversion can put this in terms of carbon dioxide equivalent. Since CO2 is 12/44 carbon by weight, it can be calculated that every ton of aluminum cans produced has a carbon footprint equal to 8.30 short tons of carbon dioxide equivalent (CO2E).

Also found in this report was data on waste management methods, which was used to account for the effects of recycling, incinerating, or landfilling on the carbon footprint of a lean manufacturing process. The EPA generated a table of relative carbon emissions for various methods of disposal, including recycling, landfilling, and combustion. These emissions were calculated from the moment of disposal, and in some cases account for credits, which measure, for instance, the emissions saved when replacing virgin inputs with recycled material. Because of these credits, the recycling option for most materials is represented by a negative number. It is beyond the scope of this research to account for credits, and therefore the emissions from garbage in this research will reflect a broader view, accounting for the manufacture and disposal of the material, as shown in Table 8.6 and Table 8.7. The full table of conversion factors appears in Table 8.8. Appendix A displays these conversion factors in context of the lean wastes they relate to.

Table 8.11. Garbage Emissions Conversion Factors

Garbage disposal material	type	MTCE/ton manufacture	MTCE/ton, from moment of discard Recycling	Combustion	Land-filling
aluminum		2.24	-3.70	0.02	0.01
steel		0.87	-0.49	-0.42	0.01
copper		2.00	-1.34	0.01	0.01
plastic	HDPE	0.49	-0.38	0.25	0.01
	LDPE	0.62	-0.46	0.25	0.01
	PET	0.57	-0.42	0.30	0.01

Table 8.12. Garbage Emissions Conversion Factors (2)

MTCE/ton, including manufacture			lb. CO2E/lb, including manufacture		
Recycling	Combustion	Land-filling	Recycling	Combustion	Land-filling
-1.46	2.26	2.25	-4.91	7.59	7.56
0.38	0.45	0.88	1.28	1.51	2.96
0.66	2.01	2.01	2.22	6.75	6.75
0.11	0.74	0.50	0.37	2.49	1.68
0.16	0.87	0.63	0.54	2.92	2.12
0.15	0.87	0.58	0.50	2.92	1.95

8.3. Incorporating Green Wastes in Value Stream Mapping

Already a proven tool for recording material and information flows, as well as timing and inventory data of a process, value stream mapping is a logical way to identify the wastes to be converted into carbon emissions [19, 20]. To this end, additional data must be selected for inclusion in the current state value stream map.

Possibly the most prevalent green waste is energy, which is used to operate machinery, computers, and to provide heat and light. It is therefore important to incorporate information on the power, time, and energy source of each step in the process. As described in Section 8.1, energy is also related to inventory. Value stream maps already track inventory flow, so by adding details of energy usage to heat, cool, and light the storage space along with the percentage of space the inventory from each value stream activity occupies, a fraction of the energy waste can be appropriated to each batch of inventory.

Materials and garbage are also significant green categories, yet are not well represented in standard value stream maps. Weights of raw materials and scrap, or anything that is discarded, should be recorded by material type and method of disposal.

Transportation is generally included on value stream maps as far as final shipping to the customer. It is an important logistical step of the process, and also a source of green waste. In order to simplify measurements, the weight and distance of each shipment, along with the method of shipping, should be noted on the current state value stream map.

Table 8.13. Green Waste Conversion Factors

Green Waste			Conversion Factor		
Energy	**heating fuel**	**electricity source**	**lb CO2E per kWh**		
	natural gas		0.40		
		average	0.44		
	electricity	fossil fuel average	0.64		
		coal	0.72		
Material	**material**	**type**	**lb. CO2E/lb.**		
	cardboard		0.81		
	paper	mixed	0.97		
		HDPE	1.65		
	plastic	LDPE	2.08		
		PET	1.92		
Garbage	**material**	**type**	**Combustion**	**Land-filling**	**Recycling**
			lb. CO2E per lb. material		
	aluminum		2.26	2.25	0
	steel		0.45	0.88	1.28
	copper		2.01	2.01	2.22
		HDPE	0.74	0.50	0.37
	plastic	LDPE	0.87	0.63	0.54
		PET	0.87	0.58	0.50
Transportation		**method**	**lbs. CO2 per ton-mile**		
	air		1.7739		
	sea		0.0887		
	ground	truck	0.3725		
		train	0.2306		

8.4. Summary of Implementation

The method developed in this research can be implemented into a company's production process in a few low effort steps.

First, a value stream is outlined in the traditional lean fashion, as in *Learning to See* [18]. During the data collection phase of the current state map, green waste metrics are recorded in addition to the usual data. These metrics are noted below in Table 8.14. In short, green waste metrics should focus on energy, material, garbage, and transportation for each value stream activity and can be recorded on the VSM. It is important to include the inventory subcategory of energy, which requires data on energy use in the storage area, as well as the percentage of that area used by the inventory from each activity.

Once the data is obtained, green metrics are plugged into the conversion table and combined with the conversion factors to translate the various metrics into their CO2E equivalents. This will provide a carbon footprint for the company, and allow them to see the relative effects of various wastes. Such comparisons will be helpful in determining which reductions will have the most impact on emissions.

At this point the lean waste reduction process continues as usual. A future state map is outlined, following the lean principles of creating flow and establishing pull [18, 25]. The future state is implemented, and thus becomes the new current state. After a time – a matter of weeks or months to establish the new state – a new current state value stream map is created in order to record the new data. New current state data is converted to CO2E and then compared to the original current state in order to track the green effects of lean improvements.

Table 8.14. Addition Data for Value Stream

Green Waste	Unit of Measure	Required Info	
Energy	kWh	source	Storage energy, %
Material	lbs.	type	
Garbage	lbs.	type	disposal
Transportation	tons	miles	mode of transport

9. Case Study

In order to illustrate the method proposed in this paper, a case study was performed using an example value stream found in *Learning to See* [18]. The current state value stream map, shown in Figure 9.1, is based on a fictional company manufacturing stamped-steel steering brackets for cars. This example is of a standard value stream map and therefore does not include green metrics. This case study uses data from the VSM, additional information found in *Learning to See*, and some assumed values in order to demonstrate the proposed method. In practice all of this information will be collected together in a walk through of the value stream, but using an existing VSM also highlights the data missing from the standard tool that is needed to make green calculations. This example will evaluate each value stream activity for green wastes and record the relevant data to be converted to CO2E emissions.

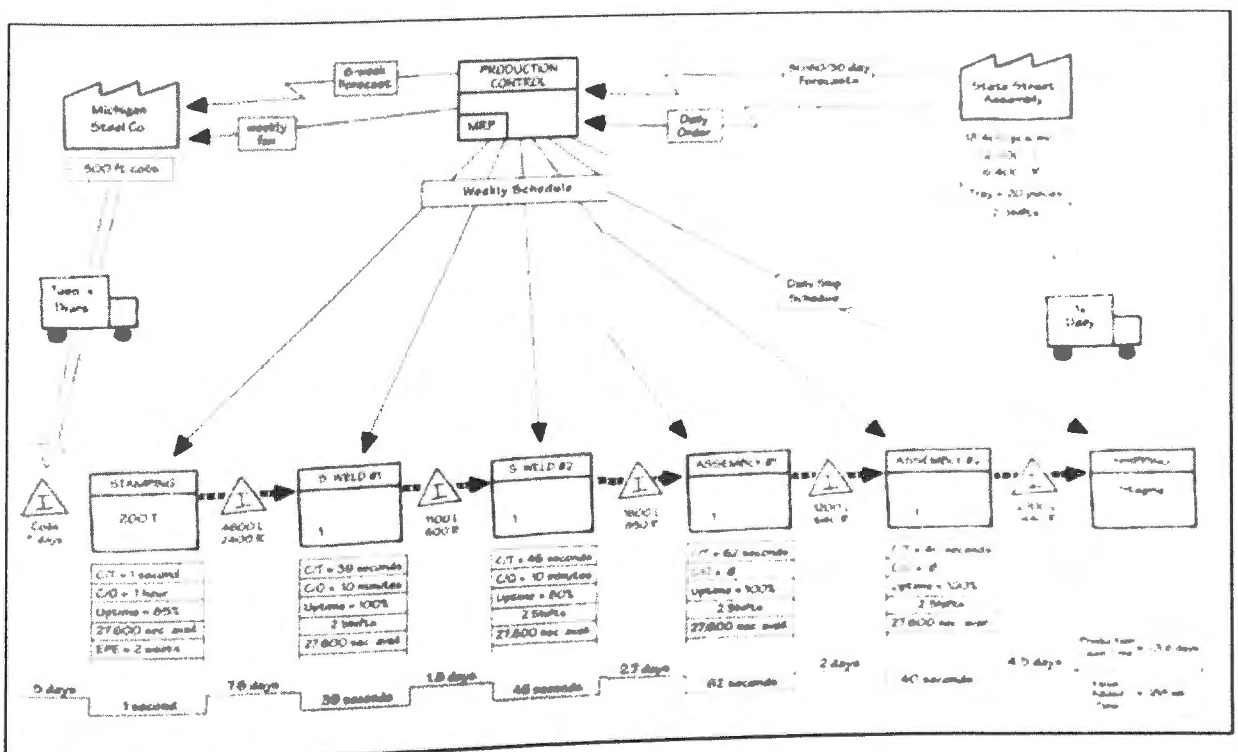

Figure 9.1. Example Value Stream Map

The receiving portion of the VSM shows 500 ft coils of steel arriving by truck every Tuesday and Thursday. Those coils are stored for five days before moving to Stamping. From this information it is evident that there is both transportation and energy waste (by way of inventory) in this step. If each coil weights one ton and is shipped 30 miles by truck, using the conversion factor from Table 8.8 it is calculated that this accounts for 11.18 lbs. of CO2 twice a week. The weight and distance data is recorded on the VSM, as shown in Figure 9.3, and then entered on a spreadsheet, such as the one in Appendix B, to simplify calculations.

Inventory data for this step must also be recorded. Suppose lighting and heating the storage area requires 10 kW of electricity and the coils occupy 40% of the storage area for five days. With a conversion factor of 0.44 lbs. CO2E per kWh, storing these coils accounts for 140.80 lb CO2E over five days. Inventory is calculated in a similar manner throughout the remaining value stream activities.

Stamping includes two shifts, or sixteen hours, of machine use. If the stamping machine uses 11 kW of electricity, its CO2E emissions can be easily calculated with the use of conversion factors. This value stream activity also produces garbage – scraps of steel that are collected and sent to be recycled. Assuming 75 lbs. of steel each day and given recycling accounts for 1.28 lbs. CO2E per lb. steel, that is 96 lb. CO2.

This value stream map shows that finished products are shipped daily, at a total of 18,400 pieces each month, in trays of 20 (a total of 920 trays). In order to calculate the carbon footprint for this step we must know the shipping method, weight and distance of the shipment, none of which is included in this map. Assuming that 30 trays totaling 0.5

tons are shipped by truck 100 miles each day, we can calculate using the conversion factor (see Table 8.8) that 18.625 lbs. of CO2 are emitted by this process each day.

Overall, this case study shows an example of a standard value stream map not providing all of the necessary data to calculate emissions, although it does show the capability to do so. By including the additional data identified, value stream mapping is a valuable tool in quantifying carbon footprints.

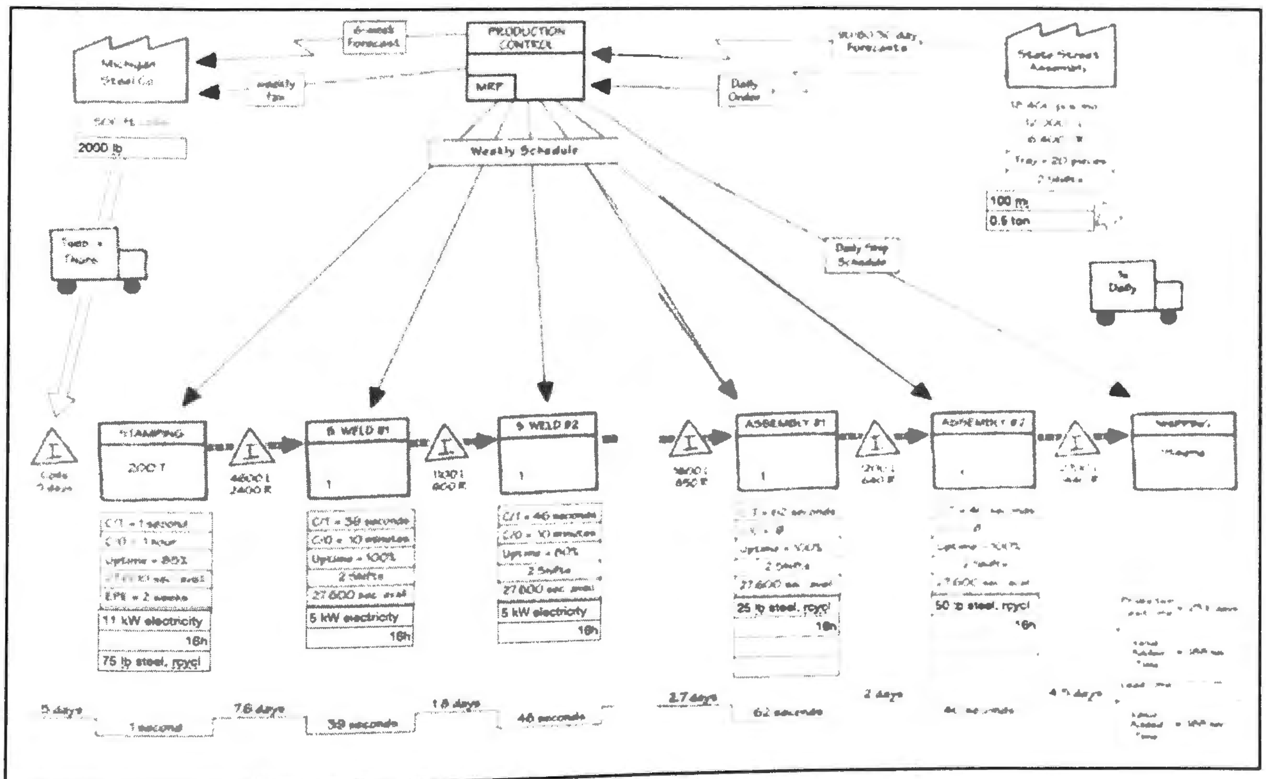

Figure 9.2. Example Value Stream Map with Green Data

10. Conclusions

This paper demonstrates how the carbon footprint of a manufacturing process can be measured by viewing green wastes as an outcome of lean waste and including additional data in the traditional value stream mapping process. The unit conversions provided allow companies to utilize information directly from their value stream map. Focusing on emissions in terms of lean waste and utilizing existing tools such as value stream maps with only slight modifications allows for results with little additional effort on the part of these companies. By comparing current states over time, companies can see the amount of carbon emissions that have been saved.

Given the impending legislation on emissions regulation, as well as growing consumer demand for green products, it is more important than ever for companies to reduce their environmental impact. A step has been made toward carbon measurement using lean waste principles. Lean manufacturing technology can serve as a mechanism to make companies compliant with impending legislation.

11. Future Work

The initial efforts in quantifying the carbon footprint of lean wastes have been outlined in this paper, yet there is still much work that can be done to advance the technique. Conversion factors must be validated to ensure accuracy. More options for materials, including hazardous wastes, should be added, and further organizing these metrics into an integrated calculator tool will greatly help companies in accessing the information. Additionally, the value stream mapping procedure of green waste identification must be standardized. At present this technique is intended for comparing green waste before and after initiating lean changes, and is not meant to fully address potential government regulations. With further study this first step in quantifying green waste from lean categories will prove a significant advance in terms of both lean and green manufacturing.

APPENDIX

CONVERSION FACTORS LISTED BY LEAN WASTE

			method	**lbs. CO2 per ton-mile**		
Transport	Transport-ation	air		1.7739		
		sea		0.0887		
		ground	truck	0.3725		
			train	0.2306		
	Material	**material**	**type**	**lb. CO2E/lb**		
		cardboard		0.81		
		paper	mixed	0.97		
		plastic	HDPE	1.65		
			LDPE	2.08		
			PET	1.92		
Defects	Garbage	**material**	**type**	**Recycling**	**Combustion**	**Land-filling**
				lb. CO2E per lb. material		
		aluminum		0	7.59	7.56
		steel		1.28	1.51	2.96
		copper		2.22	6.75	6.75
		plastic	HDPE	0.37	2.49	1.68
			LDPE	0.54	2.92	2.12
			PET	0.50	2.92	1.95
	Energy	**heating fuel**	**electricity source**	**lb CO2E per kWh**		
		natural gas		0.40		
		electricity	average	0.44		
			fossil fuel average	0.64		
			coal	0.72		
Over Production	Energy	**heating fuel**	**electricity source**	**lb CO2E per kWh**		
		natural gas		0.40		
		electricity	average	0.44		
			fossil fuel average	0.64		
			coal	0.72		
Inventory	Energy	**heating fuel**	**electricity source**	**lb CO2E per kWh**		
		natural gas		0.40		
		electricity	average	0.44		
			fossil fuel average	0.64		
			coal	0.72		
Motion	Garbage	**type**	**disposal**	**Recycling**	**Combustion**	**Land-filling**
				lb. CO2E per lb. material		
		aluminum		0	7.59	7.56
		steel		1.28	1.51	2.96
		copper		2.22	6.75	6.75
		plastic	HDPE	0.37	2.49	1.68
			LDPE	0.54	2.92	2.12
			PET	0.50	2.92	1.95
Over Processing	Energy	**heating fuel**	**electricity source**	**lb CO2E per kWh**		
		natural gas		0.40		
		electricity	average	0.44		
			fossil fuel average	0.64		
			coal	0.72		
Waiting	Energy	**heating fuel**	**electricity source**	**lb CO2E per kWh**		
		natural gas		0.40		
		electricity	average	0.44		
			fossil fuel average	0.64		
			coal	0.72		

EXAMPLE CURRENT STATE CARBON FOOTPRINT DATA SHEET

Current State

						Conversion Factor	lbs. CO2E
Storage Room		*Type*	*Power (kW)*				
		electricity	10				
			Receiving				
Transport-ation		*Method*	*Distance (mi)*	*Weight (ton)*	*Frequency*		
		truck	150	1	2 x week		
Energy	**Inventory**	*Parts (L)*	*Parts (R)*	*Time (days)*	*space (%)*		
		Coils		5	40%	0.44	140.80
			Stamping				
Energy	**Equipment**	*Source*	*Power (kW)*	*Time (hour)*			
		electricity	11	16		0.44	77.44
	Inventory	*Parts (L)*	*Parts (R)*	*Time (days)*	*space (%)*		
		4600	2400	7.6	10%	0.44	53.50
Garbage		*Type*	*Weight (lb)*	*Disposal*			
		steel	75	recycle		1.28	96.00
			S. Weld #1				
Energy	**Equipment**	*Source*	*Power (kW)*	*Time (hour)*			
		electricity	5	16		0.44	35.20
	Inventory	*Parts (L)*	*Parts (R)*	*Time (days)*	*space (%)*		
		1100	600	1.8	10%	0.44	12.67
			S. Weld #2				
Energy	**Equipment**	*Source*	*Power (kW)*	*Time (hour)*			
		electricity	5	16		0.44	35.20
	Inventory	*Parts (L)*	*Parts (R)*	*Time (days)*	*space (%)*		
		1600	850	2.7	10%	0.44	19.01
			Assembly #1				
Garbage		*Type*	*Weight (lb)*	*Disposal*			
		steel	25	recycle		1.28	32.00
Energy	**Inventory**	*Parts (L)*	*Parts (R)*	*Time (days)*	*space (%)*		
		1200	640	2	10%	0.44	14.08
			Assembly #2				
Garbage		*Type*	*Weight (lb)*	*Disposal*			
		steel	50	recycle		1.28	64.00
Energy	**Inventory**	*Parts (L)*	*Parts (R)*	*Time (days)*	*space (%)*		
		2700	1440	4.5	20%	0.44	63.36
			Shipping				
Transport-ation		*Method*	*Distance (mi)*	*Weight (ton)*	*Frequency*		
		truck	100	0.5	1 x daily	0.3725	18.63
Material		*Type*	*Weight (lb)*				
		cardboard	10			0.81	8.10
				TOTAL LBS CO2E			**669.99**

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