Use of Composite Environmental Indicators in Residential Construction

by

Terianne C Hall

Submitted to the Department of Mechanical
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Signature of Author..
Department of Mechanical Engineering
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Certified by..
John E. Fernández
Associate Professor of Building Technology
Thesis Supervisor

Accepted by ....
John H. Lienhard
Professor of Mechanical Engineering
ME Undergraduate Officer

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ABSTRACT

As a result of the damage caused by hurricane Katrina in August 2005, fifty percent of New Orleans residential housing was destroyed or severely damaged. A systems model is being developed at MIT for promoting resource efficient housing in New Orleans. The model attempts to capture the urban metabolism of the city by tracking the material and energy flows required of various possible reconstruction scenarios. The model is meant to act as a tool for policy makers to identify the most effective construction methods for a green city. Currently, the model is programmed to provide output values for material use, energy consumption and labor hours during the construction, use, and end-of-life phases of portions of the city's housing stock. While these quantitative results are useful for specialists to understand a given scenario, they are not useful for policy makers.

My thesis project will focus on comparing the merits and drawbacks of applying various standard indicators to New Orleans construction methods. This includes, but is not limited to, Gross Domestic Product per capita and Species Diversity. Next, my work with this project will focus on assessing existing composite indicators based on their relevance to the model and their usability by policy makers. Understanding the merits and downfalls of various composite indicators will allow policy makers to choose an appropriate metric for comparing construction option, and make informed decisions about incentive programs for the various stages of reconstruction in New Orleans. It is the intention of the project to find indicators that can be generalized for use in other locations in conjunction with future models of urban metabolism yet to be developed.

Thesis Supervisor: John E. Fernández
Title: Associate Professor of Building Technology

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1.0 Introduction

As a result of the damage caused by hurricane Katrina in August 2005, fifty percent of New Orleans residential housing was destroyed or severely damaged. For the past year, Professor John E. Fernández, MIT Master's student David Quinn, and the engineering firm of Camp Dresser McKee, Inc. have been working with the New Orleans Office of Recovery Management to create a working systems model for promoting resource efficient housing in New Orleans. The model attempts to capture the urban metabolism of the city by tracking the material and energy flows required of various possible reconstruction scenarios. Ultimately, it is meant to act as a tool for policy makers to identify the most effective construction methods for a green city.

The model currently provides output values for material use, energy consumption and labor hours during the construction, use, and end-of-life phases of portions of the city's housing stock. While these quantitative results are useful for specialists to understand a given scenario, they are not useful for policy makers. These outputs can be combined to form indicators that weight the outputs to form an overall measure of sustainability. Industrial ecologists have developed dozens of indicators to assess sustainability, however it is unclear which indicators would be most appropriate for assessing a large–scale residential reconstruction project like the New Orleans model.

My thesis project will focus on comparing the merits and drawbacks of applying various standard indicators to New Orleans construction methods. This includes, but is not limited to, Gross Domestic Product per capita and Species Diversity. Next, my work with this project will focus on assessing existing composite indicators based on their relevance to the model and their usability by policy makers. An example of a well-known composite indicator is the ecological footprint. This indicator translates an individual's resource consumption into the amount of land necessary to absorb the carbon dioxide emissions created the annual consumption of these resources. An ecological footprint calculation can also measure the overall environmental impact of a community, a city or even a nation. [10] Understanding the merits and downfalls of various composite indicators will allow policy makers to choose an appropriate metric for comparing construction option, and make informed decisions about incentive programs for the various stages of reconstruction in New Orleans. It is the intention of the project to find indicators that can be generalized for use in other locations in conjunction with future models of urban metabolism yet to be developed.

2.0 Background

The global population is increasing and becoming more affluent. These factors have led to increased energy consumption across the globe, which has led to a decrease in the Earth's stock of natural resources. Each year, humans consume more renewable resources than the Earth can produce in one year, while continuing to consume the ever-decreasing stock of nonrenewable resources. This trend is dangerous to the stability of the entire ecosystem because it has led to a decrease in the Earth's stock of natural capital. When the natural capital of the Earth reaches zero, the Earth is considered dead and life will not be able to survive on its surface. [16]

Figure 1 displays three possible trends for the consumption of the Earth's total resources. Each trend is approaching an asymptote, meaning that in order the life that Earth supports to survive Earth will have to become a Type III ecology. This means that the rate of resource extraction from the Earth must be less than or equal to the rate of production of the Earth's natural resources. As nonrenewable resources are consumed, renewable resources must continue to be grown to replace them. A Type III ecology system receives energy from the environment and recycles materials within the system so that there is no waste output to the environment. While humans are far from achieving such a lofty goal, it is clear from Figure 1 that the environmental decisions made in the 21st century (labeled B in Figure 2.0.1) are vital to maximizing the natural capital remaining once a Type III ecology is achieved. [4]

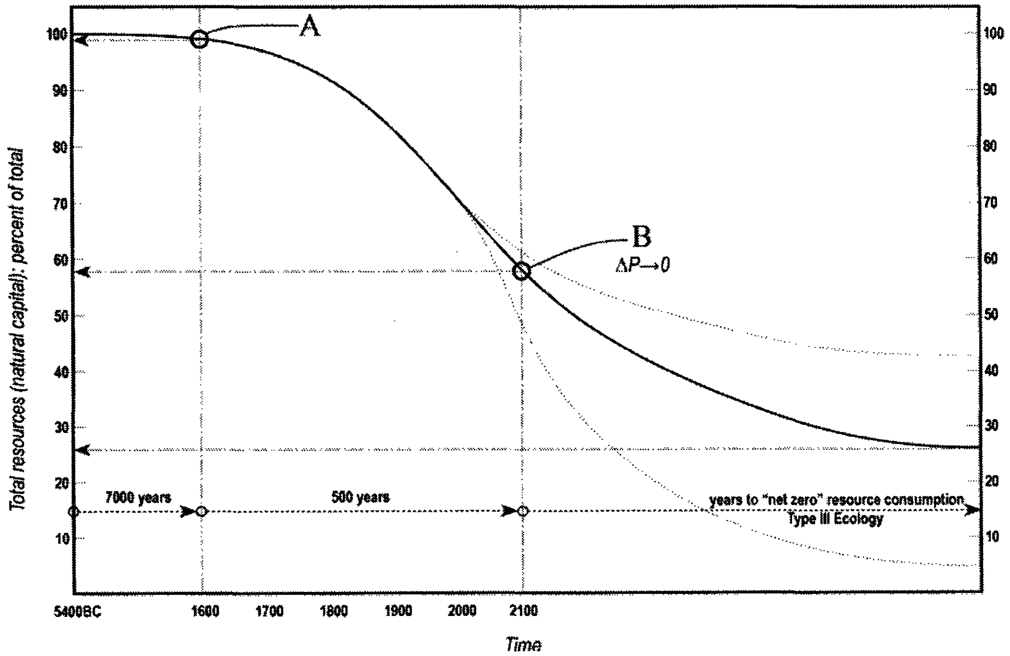

Figure 2.0.1: Three Scenarios for a Type III Ecology [4]

An apparent obstacle that impedes humanity's progress towards a Type III ecology is a general ignorance towards the subjects of sustainability and the environment. While many construction materials are marketed as "green" and "sustainable," there are few existing standards available to environmentally compare the various construction options available to a region. As reconstruction in New Orleans begins, it is vital that there be a method to compare the sustainability of construction materials such as wood, steel stud, and concrete. This comparison must take into consideration the entire life of the building including its construction, use, and deconstruction. By making this comparison in the system model, before the design of these homes is fixed, policy makers can offer financial incentive to those citizens who choose to construct sustainable homes.

3.0 Standard Indicators

When choosing an indicator as a measure of sustainability, one must first select what quantities are most important to be tracked. In the broadest sense, one may consider what is essential to the human survival. For example, humans require an air composition that is breathable and amiable climate temperatures. These two conditions alone are affected by various metrics such as carbon dioxide emissions, energy consumption, and the way in which resources are harvested and refined.

Many standard environmental indicators are agent based, in that they can easily be assigned on a per capita basis, however they are often less effective in assessing products, services, or in the case of New Orleans, residential construction.

When considering the rebuilding of New Orleans, there are also various subtleties that must be addressed before ranking housing types in order of sustainability. For example, while a wood framed house with fiberglass insulation may have a lower embodied energy than a house made from SIPs, it may require the use of more material or be less insulating, and thus require more energy to climate control during the use of the house. Another consideration may be the type of energy used to create the construction materials. If the SIPs were made in a factory powered by photovoltaic cells, is that better than the wood that was cut to size in a mill that uses coal to provide energy? What if the SIPs were shipped from across the country on a diesel burning truck, while the wood was grown locally? One must also consider the deconstruction of these structures – certain materials are much more likely to be recycled than others. Additionally, skilled workers are required to erect certain housing types, thus encouraging these housing types may be beneficial for New Orleans rebuilding a robust workforce. Relevant social concerns must be weighed against the idea of sustainability. These questions only begin to examine the complexity of assessing the question of sustainable housing.

3.1 GDP/capita (gross domestic product per capita)

According to Ehrlich and Holdren, affluence plays an important role in determining a region's environmental impact. Qualitatively, they assert:

$$I = P \cdot A \cdot T, \tag{1}$$

where *I* is environmental impact, *P* is population, *A* is affluence, and *T* is technology. [2] Stating that affluence is directly related to environmental impact implies that a wealthy person is likely to consume more materials and emit more waste than a person with less money. The wealthy person can afford to buy items that are beyond a human's baser needs, and the energy used during the manufacturing and operation of these items significantly contributes to the global consumption of natural capital. Though the "IPAT" equation's relationship is usually considered qualitatively, national affluence can be measured quantitatively by understanding the gross domestic product per capita of a nation.

The United Nations Statistic Division monitors the gross domestic product (GDP) and the population of every country on earth. GDP is defined as the "sum total value-added of all production units included all taxes and subsidies on products which are not included in the valuation of output." When the GDP is divided by the national population, a measure of relative affluence among nations is achieved. As the GDP/capita of a country increases, historically the average person in the country can afford to buy more manmade technology, and consequently this person has a larger environmental impact. [14]

While measuring affluence is an interesting first step to quantifying the environmental impact of a nation, this indicator cannot standalone. It does not provide suggestion towards a solution for policy makers because capitalist societies universally agree that controlling affluence is not an option. GDP/capita is an important performance indicator for the economic situation of a nation, however it does not directly address the environmental impact of production. In some nations, a high GDP could be the result of inventing and selling technologies with a low environmental impact ($T > 1$), causing the high GDP to signify a low environmental impact. The indicator does not address material or energy consumption, thus it is not a good indicator for environmental impact.

Because New Orleans is only a part of the nation, it would be interesting to compare the affluence of its population to the affluence of the average member of the United States. Using this indicator in tandem with an indicator that monitors energy consumption would prove to be an interesting comparison. Once the city is reconstructed, one can determine the energy consumption on an average day is greater than that of an average city, and this can be compared to the city's affluence.

GDP/capita would not be a good indicator for the systems model because it does not directly address environmental concerns associated with new construction.

3.2 Energy Use/capita and embodied energy

Energy use per capita is another standard indicator that is used to measure environmental impact. It is calculated annually and the unit of measurement is generally gigajoules/year for each person. Selecting a region and tabulating all of the electricity that was generated in the region during an entire year is the first step towards finding energy use/capita. This number can then be divided by the number of people in the region to find an average indicator value. This value is known as the energy intensity of the society. [14]

An alternative to calculating a regional value for energy use/capita is to focus on an agent based calculation. This approach is much more time intensive, but can be more useful to an individual who is interested in learning how his environmental impact compares with the rest of his region or nation. [15]

Energy is necessary to provide products and services to societies. Using fossil fuels as energy, however, has led to large environmental impacts caused by the development of societies. These impacts are due to all parts of the energy generation process including the extraction of the ores and emissions of greenhouse gases when burning the ores. Though policy makers should not attempt to stop the development of societies, they must attempt to foster development in a less energy intensive way.

One important limitation of this indicator is that it does not specify the composition of the energy consumption of the society. If a nation has a large energy use/capita, but much of its electricity generation is done with windmills, this consumption is probably more sustainable than that of the average society because it lacks many of the harmful emissions associated with burning fossil fuels. Even though this indicator is relevant for measuring the total consumption of a society, it does not measure the overall effect of this energy use on the planet. Though one society may have a higher energy use/capita than another, the first society has no reason to decrease consumption because the metric does not set a limit on consumption. [14] It is unclear whether the consumption of either country is sustainable or unsustainable. Though this indicator does not entirely address the question of sustainability, industrial ecologists have used it to create effective composite indicators that address the limits of the Earth's ecosystem.

Because the reconstruction of residential housing in New Orleans should not consider energy use on a per capita basis, this indicator can be calculated on a per house basis. The indicator will then allow for a comparison of the energy use required in constructing, using and deconstructing various housing types.

Using David Quinn's compilation of information about various house types and sizes in New Orleans, I was able to calculate information about material necessary to construct the average New Orleans residence for four housing types: wood stud construction, steel frame construction, aerated autoclave concrete blocks (AAC), and structurally insulated panels (SIPs). The results are displayed in Table 3.2.1. [9]

Material	Wood stud (kg/m^2)	Steel frame (kg/m^2)	AAC (kg/m^2)	SIPs (kg/m^2)
Timber	69.6	0.0	62.3	54.5
OSB	39.0	39.0	28.1	43.2
Gypsum	39.8	39.8	39.8	39.8
Asphalt	11.9	11.9	11.9	11.9
Vinyl	11.7	11.7	0.0	11.7
Fiberglass	1.2	1.2	0.6	0.6
Building paper	0.8	0.8	0.0	0.8
Felt	0.9	0.9	0.9	0.9
Steel	0.0	6.4	0.0	0.0
AAC	0.0	0.0	173.5	0.0
Stucco	0.0	0.0	27.8	0.0
EPS	0.0	0.0	0.0	8.9

Table 3.2.1: Material required for various housing types in kg per squared meter [9]

The exterior walls of each averaged residence were considered to be 10% glazed, and the floor area of each home was 170.75 squared meters. [8]

Using this data it was possible to assess the embodied energy associated with each material of each housing type. This calculation includes the energy associated with finding and processing the construction materials in a factory. The energy required to transport them to the construction site is not included in these calculations. These assumptions are known as cradle to gate, because they consider the life of the material until it leaves the gate of the factory. [5] The results of these calculations are displayed in Figure 3.2.1. The embodied energy values for these calculations were from the Inventory of Carbon and Energy survey conducted by the University of Bath. Because the embodied energy values were calculated in Europe, the results displayed in

Figure 3.2.1 should be altered slightly when further research is done into local New Orleans construction materials. [5]

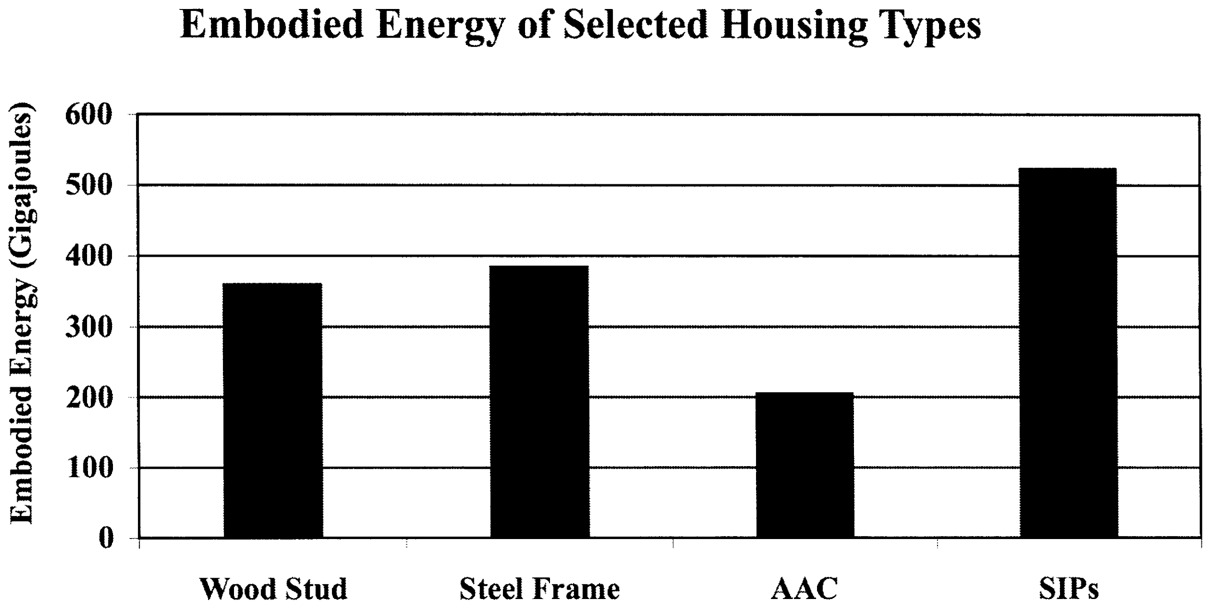

Figure 3.2.1: Comparison of the embodied energy of select housing types in New Orleans

The AAC blocks have the lowest embodied energy of any of the selected housing types. The embodied energy of an AAC house is approximately half of the other three housing types. While this data may show that the AAC house is the most sustainable solution for New Orleans reconstruction, the calculations do not consider energy savings that may be inherent during the use and deconstruction phases of the other housing types. For example, if the SIPs house is much better insulated than the AAC house, it will tend to have lower energy consumption over the lifetime of the building. This information will be available from the systems model, and future work could include creating a more complete comparison of the energy consumption of the four housing types over the lifetime of the building.

3.3 CO_2 Emissions/capita and embodied carbon

Tracking carbon dioxide emissions per capita is more telling than tracking energy use per capita across the nation. While energy use monitors energy consumption, carbon dioxide translates this consumption into a measure of environmental impact. Carbon dioxide is a dangerous greenhouse gas that is being emitted into the Earth's atmosphere at unsustainable rates. This metric takes the first step towards quantifying how unsustainable these emissions are. [3]

Like the energy use/capita metric, CO_2 emissions/capita is limited in its assessment because it does not indicate the overall effect of the carbon dioxide emissions on the Earth's ecosystem. In order for the indicator to measure sustainability it must express more the weight of emission in tones, it must be able to express how much these emissions are affecting the environment. Unlike the energy indicator that counts 1 Joule generated from burning fossil fuel the same as 1 Joule generated from wind power, CO_2 emissions/capita is able to discern the idea of sustainability in electricity generation.

This metric can be applied to the construction materials of the New Orleans model in the same way that energy use was applied. Materials have embodied carbon values that represent the amount of carbon dioxide emitted from cradle to gate. These values were collected from the Inventory of Carbon and Energy survey conducted by the University of Bath. Once again, the embodied carbon values were calculated in Europe, thus the results displayed in Figure 3.3.1 should be altered slightly when further research is conducted on local New Orleans construction materials. [5, 8, 9]

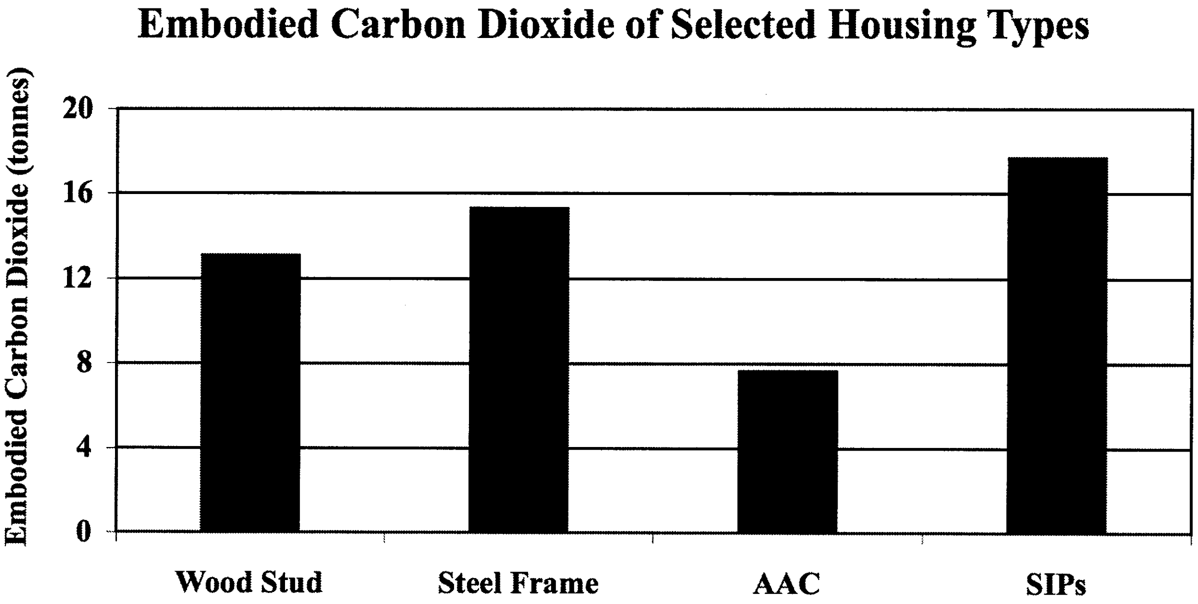

Figure 3.3.1: Comparison of the embodied CO_2 of select housing types in New Orleans

The results displayed in Figure 3.3.1 were tabulated using the average house assumptions outlined in Table 3.2.1 and the Energy use/capita section of the report. [8, 9] The AAC house has the lowest embodied carbon value, while the SIPs house has the highest value. These values may imply that the electricity used to create AAC blocks happens to be from a renewable resource, there is less processing involved in producing the materials for an AAC house, or the production processes are much more efficient.

Once the systems model is complete, these values calculations could be extended to get a total CO_2 emissions/house throughout its construction, use, and deconstruction phases.

3.4 Species Diversity

Species diversity is a metric that enables humans to understand how much of an effect they are having on an ecosystem. By erecting buildings and infrastructure on undeveloped land, humans continually change the delicate ecosystems that are home to other living organisms. These changes often result in a reduction of the number of species in a given region due to overpopulation or habitat destruction. Because species loss is irreversible, it is important to monitor the species diversity of a region to ensure that new construction has a minimal effect on the existing ecosystem. [7]

Species richness can be defined as the total number of species of organisms that occupy a defined unit of land. While it is intuitive that increasing the area of the land considered would increase value of species richness, ecologists have experimentally discovered a simple power law that governs the relationship between species richness and area. [7]

$$S = c\,A^{z}, \tag{2}$$

where S represents the species richness or total number of species, A represents the area of the land surveyed, and c and z are coefficients that must be determined experimentally for a given land type.

This metric is most useful as a comparison. A researcher must compare the region of land in question to a similar region that is considered untouched. For example, if a planned community is going to be built in a wooded area in the northwestern United States, a nearby wooded nature reserve would serve as an appropriate standard for comparison. Evaluating the wooded area with respect to a marshland would be ineffective as the species richness is not likely to be comparable. Once a suitable control zone has been found, the researcher is then able to survey sample areas of the control of various sizes. Using this data he should be able to fit his data to the power law and find the c and z coefficients. [7]

When considering a landscape that has more than one ecosystem, such as a lake that is surrounded by a forest, one may use the following formula to calculate species density:

$$D_i = \frac{S_i}{A_i^z}. \tag{3}$$

In this case, D_i represents the species density for a specific land type. If the ecosystem is untouched, the species density should remain constant for the specified type of land assuming the sample was taken on a reasonably large scale. [7]

Once the species densities have been calculated for all of the land types in the landscape, one can calculate the total species diversity. An example for a landscape that includes a lake, a forest and a desert is displayed below:

$$D_{total} = D_{lake}p_{lake} + D_{forest}p_{forest} + D_{desert}p_{desert}. \tag{4}$$

The variable p represents the proportion (from 0 to 1) of the landscape that is covered with the specified land type. By knowing the species densities of various untouched land types, one can calculate an expected species density of a landscape, and compare it to measured species densities. [7]

One important subtlety to consider when using this metric is how to compare expected species richness or species density to real data. While it may seem intuitive to simply divide the actual value by the reference value, this is not always helpful because it will often yield values that are greater than one. Though increased species density or richness for a given land size may seem like humans are having a positive effect on the landscape, it is most likely foreboding a decrease in species density and richness. For example, when humans build a new community in a wooded area, they are forced to clear many of the trees. The displaced creatures will generally move to what remains of their habitat, thus creating an increase in species density in the remaining wooded areas. This increase, however, is generally followed by overpopulation and competition for limited resources. The species that are able to adapt to new conditions or fight for remaining resources will survive, while the weaker or less robust species will die. This phenomenon is referred to as unsustainable overloading. [7]

A better way to compare species richness for a given area, or species density for a given landscape is to calculate the error between land that has been changed by humans and the natural ecosystem or control. This calculation is shown below for species richness:

$$M_i = 1 - \left(\frac{|S_i - S_n|}{S_n} \right), \tag{5}$$

where M_i is a value from 0 to 1 that represents how affected the land type is. A value of one means that humans have not influenced the landscape at all, where as a value of zero means that the landscape is virtually barren. If the comparison is done using species richness, one must take care to use control values that were calculated using the same sample area. It is also important to know the values that go into calculating Mi because an increase in species richness will require a different response than a decrease in species richness. [7]

These formulas can also be focused on specific taxa that have intrinsic value to humans and are easy to survey such as birds, wildflowers and butterflies. These values are also more effective for policy makers because it is easier to campaign to save bird species than it is to save phytoplankton species. It is likely that a bill put into effect to preserve birds will also indirectly serve to preserve the habitats of other at risk species. [7]

As humans continue to degrade the environment, one must remember to use the earliest possible values of c and z for a comparable land type because they will change as natural ecosystems are more and more affected by humanity. All of these formulas can also be applied using only native species in order to understand to what extent humans have affected the landscape by way of managing forests of planting foreign vegetation. Neglecting exotic species, however, requires historic species information about the considered land type.

It is important to note that this indicator does not designate between endangered species and thriving species, thus it should not be used as a sole species indicator. [7]

Species diversity studies would be interesting to conduct for the New Orleans area because this reconstruction period allows urban planners to decide park placement. The species density has probably also been affected by the flood, and understanding the previous ecosystem will allow planners to make informed decisions for reconstruction. These values, however, will not play a large role in the choice of residential housing types, and thus should not be included as one of the indicators in the system model.

4.0 Composite Indicators

Many of the shortcomings of the standard indicators described in section 3 were due to the fact that they were unable to compare human consumption with its overall effect on Earth's ecosystem. Composite indicators include factors that enable comparisons between two agents in addition to information regarding the overall sustainability of the agents relative to the Earth and their region. With some composite indicators, these comparisons can be expanded beyond agents to residential housing types, products, services and processes.

4.1 Ecological Footprint

The ecological footprint is probably the most widely used composite indicator. It is designed to make a large-scale comparison between the total available natural capital on earth and the demand on this natural capital by mankind. This comparison also exists on a national scale, and is generally presented as an agent based metric or per capita. [10]

The first step towards calculating the ecological footprint of a region is usually defining the population in question. All of the goods and the services that are consumed by the population must be tabulated in the manner of a life-cycle analysis. One must consider the resources necessary that were used to provide these goods and services, as well as the resources necessary to use them, and the waste generated by them or the resources necessary to dispose of them. This method of accounting is considered 'cradle to grave.' This methodology is often complex because it requires a complete list of goods and services, as well as detailed knowledge of their production. [15]

Because of the inaccuracies in tracking the life cycles of various processes, compound footprinting was developed to offer a simpler alternative to life cycle analysis. In this case, one needs to only look at the data for resource demand of a given region. [15] This eliminates the complexity that is associated with determining the end use of a product. For example, rather than tracking paper use throughout the country, one may consider the total number of trees that have been cut down, the total number of fossil fuels that have been burnt (to create energy for factories), and the total of number of petroleum that has been sold (to allow trucks to ship products). These inputs are relevant for the making of plywood as and many other products that do not need to be considered separately to calculate a national footprint.

One of the creators of the ecological footprint, Mathis Wackernagel, suggests that if mankind consumes fewer resources in a year than the Earth regenerates in a year, then the rate of consumption is sustainable. He defines six main assumptions when determining how many resources the Earth must regenerate each year to keep up with human consumption. [15]

1. Resource consumption data is tracked by national organizations, and products traded internationally are factored into the consumption of the end nation, thus,

$$\textit{ecological footprint} = \textit{domestic production} + \textit{imports} - \textit{exports}. \tag{6}$$

2. The resources available for human use is known as the Earth's biocapacity and is related to the biologically productive land necessary to regenerate those resources and assimilate resultant waste and emissions
3. Productive or global hectares (gha) are weighted in proportion to the particular land type productivity relative to the total possible productivity of the entire Earth (hectare, 100m x 100m)
4. The human demand in global hectares requires adding all areas needed to support demand from resource use and waste assimilating without double counting
5. Biocapacity can be compared to ecological footprint because they are both measured in global hectares
6. If the total human demand or global eco footprint is greater than the Earth's biocapacity then mankind is creating an ecological deficit that is characteristic of unsustainable consumption [15]

Table 4.1.1 displays recent estimates for the total number of global hectares available to mankind. These hectares are broken down by land type and are displayed with their global equivalence factor. While the area values displayed below account for approximately 25% of the Earth's total area, they are home to 80-90% of the Earth's renewable resources. [15]

Land Type	Billion gha	Equivalence Factor (gha/ha)
Cropland	1.5	2.1
Grazing/Pastures	3.5	0.5
Forest	3.6	1.4
Built-up	0.2	2.2
Marine and fisheries	2.3	0.4

Table 4.1.1: Global hectare and equivalence factor breakdown for various land types [15]

These equivalence factors are the same for the entire planed for a given year. Comparing a specific land type to the average productive hectare generates these factors. For example, it would take almost three hectares of the world average grazing land to get the biocapacity of one hectare of world average forest. Of course, the productivity of forests is different in every nation, thus each country has another set of scaling factors known as yield factors for each of the five land types. These measure the extent that the area in a given country is more or less productive than the global average for a specific land type. An example of this would be the area that would be used to graze all of the cows in England divided by the area that would be necessary using the world averages for pastures. Built up land is assumed to be agricultural land that has been settled on by humans. The discrepancy between these two land types is settled by the yield factor on a per country basis. [15]

A sample calculation for the footprint of wood use in England is expressed qualitatively below:

$$Forest_{England}(gha) = 1.4\left[gha/ha\right]\cdot\left(\frac{consumption_{England}[m^3\,wood\,used/year]}{yield_{England}[m^3\,wood\,grown/ha/year]}\right)\cdot forest\,yield\,factor_{England} \quad (7)$$

Calculating the footprint of fossil fuel consumption is a bit subtler than the calculation displayed above. Because the burning of fossil fuels releases dangerous greenhouse gases such as carbon dioxide into the Earth's atmosphere, one must consider the land area of forests needed to sequester the carbon dioxide. On average, the ocean sequesters one-third of emitted CO2, however the rest must be removed by trees via photosynthesis. One method of doing this calculation is displayed below:

$$FossilFuel[gha] = \frac{CO_2\,emissions[tonnes]\cdot(1-0.33)}{sequestration\,rate[tonnes/gha]}.\ [15] \quad (8)$$

Another important aspect to consider when calculating the footprint of burning fossil fuels is that they are nonrenewable resources. Their replacement by biomass must also be calculated by tabulating the totally energy consumption in Joules and dividing it by the round wood energy density in Joules/hectare. Wackernagel considers nuclear energy to be a fossil fuel because of the toxicity of its waste. The ecological footprint does not factor in the risk of using different fuel types. [15]

Once regional footprints have been calculated, one can find the ecological deficit of a given region in the following way:

$$\textit{ecological deficit } [gha] = \textit{ecological footprint } [gha] - \textit{biocapacity } [gha]. \tag{9}$$

This balance of natural capital is at the core of understanding the sustainability of a region's consumption via the ecological footprint. [10]

Trading with regions that have an ecological surplus can reduce deficits. If the deficits are not zeroed, then the region goes into a state of overshoot, where the quality of the land types decreases and yield factors decrease. Global hectares will become less and less productive overtime and the natural capital of the Earth will be degraded. [10, 16]

A major shortcoming of the ecological footprint as a metric is the fact that it requires the use of national data, which is based on national organizations and will likely be inaccurate. The margins of these errors are unknown. One can assume, however, that these errors are in less affluent countries, which account for a small percentage of global resource consumption. There are also grey areas in the calculation, such as the consumption of tourists and the refueling of internationally bound airplanes. [15]

The footprint cannot stand alone as a metric because a region that is approaching an ecological deficit is likely to have reductions in water cleanliness and species diversity; indicators that are not part of the footprint. The indicator does however answer the question of how much area is necessary to provide goods and services to mankind, and is this amount sustainable.

While the outcome of ecological footprint measures is generally agent based, it is possible to translate the metric to the residential housing options in New Orleans. Knowing the embodied carbon dioxide in the materials of an average house enables a calculation of the ecological footprint of the materials of the house. The assumptions used for the average house calculation is consistent with those used in earlier sections. This data is expressed graphically below. [3, 8, 9]

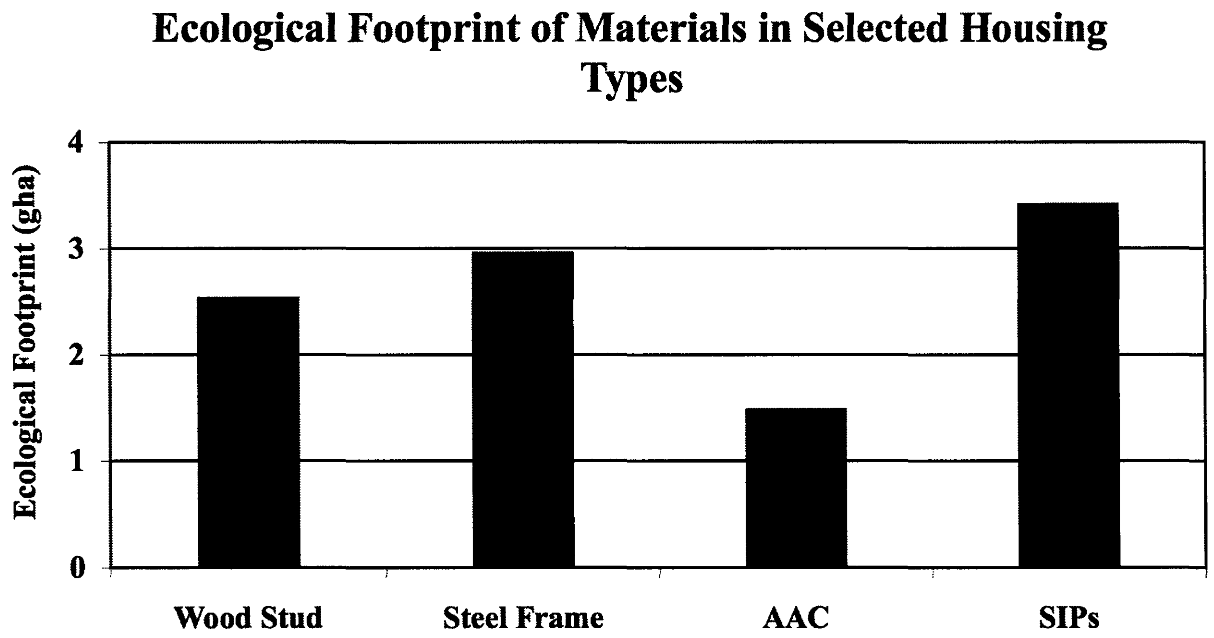

Figure 4.1.1 Ecological footprint comparison of various New Orleans housing types

Figure 4.1.1 shows that the SIPs house has the largest ecological footprint, while the AAC house has the smallest. This calculation does not consider changes in energy consumption during the use phase of the house based on better insulation or daylighting options. After the systems model has run for various housing types, the use-phase could be factored in as well. It also neglects the energy consumed in transporting the various materials. Regional yield factors and sequestration rates were unknown, thus a value of 1 tonnes/ha/year of carbon (3.47 tonnes/ha/year of carbon dioxide) was used. It was assumed that one-third of the carbon dioxide was sequestered by the ocean. [15]

4.2 Ecological Rucksack

Another metric that has become a popular metric in the wake of dematerialization is the ecological rucksack. Schmidt-Bleek defines the ecological rucksack as "the total quantity (in kg) of natural material (M) that is disturbed in its natural setting and thus [is] considered the total input (I) in order to generate a product – counted from the cradle to the point when the product is ready for use – minus the weight (in kg) of the product itself." [12, 13]

When quantifying the disturbed natural material associated with the 'hidden flows' to acquire raw materials, Schmidt-Bleek suggests dividing the information into five environmental sectors: water, air, soil, renewable biomass (known as biotic) and non renewable (known as abiotic). Disturbed water involves the contamination of both surface and ground water. Air is considered disturbed when it has been tainted by combustion or chemical and physical transformations. Disturbed soil includes erosion and mechanical earth movement. Biotic raw materials include the consumption of plant or animal biomass and abiotic ram materials include minerals (sand, ores, granite) and fossil fuels (coal, petroleum). Schmidt-Bleek asserts that most products have non-renewable rucksacks of 30 times their mass. [12, 13]

The ecological rucksack allows engineers to consider the material intensity of the hidden material flows. When deciding between two materials for a given product or house, it is considered more sustainable from a dematerialization standpoint to select a raw material that would require a lower ecological rucksack for the product as a whole.

The rucksacks for non-renewable resources are often the most relevant, as they include fossil fuel consumption. Ecological rucksacks for various construction materials are displayed in Table 4.2.1.

Material	Abiotic Rucksack (kg/kg)
Round wood	1.2
Glass	2
Plastic	2 – 7
Steel	7
Paper	15
Aluminum	85
Copper	500
Platinum	500,000

Table 4.2.1: Abiotic rucksack of various raw materials [12, 13]

While the ecological rucksack provides a first step towards understanding the materials disturbed, it is not a complete measure of the material intensity of a product or service. The ecological rucksack neglects the refining and transporting of these raw materials, as well as the energy consumed during manufacturing. Additionally, the ecological rucksack fails to answer the question of the material input necessary to use a given product or provide a selected service.

By combining the knowledge of rucksacks with the material flows involved in production and use of products, a more applicable metric, MIPS, is formed. [11, 12, 13]

4.3 MIPS

The metric of material input per unit service, known as MIPS, is a good indicator for measuring the ecological stress of goods and services from cradle to grave. The basic calculation necessary to find the MIPS of a product or service requires summing the mass of all of the material that enters the product and dividing this value by all of the services received from the product during its lifespan. The material entering the product includes the resources necessary to make the product, those disturbed by doing so (ecological rucksack), and the resources involved in the manufacture, transport, storage, package, use and disposal of the product. [1]

MIPS is an interesting metric because it looks beyond the obvious calculations engineers do when making a material selection. Schmidt-Bleek cites the following example: while an aluminum car seems like a more sustainable option than a steel car because it is lighter, and thus requires less energy to put into motion, it must be driven for 600,000 km before it has a lower MIPS value because of the high material intensity of steel. This is due to the high ecological rucksack associated with aluminum. (Tables 4.2.1 and 4.3.1) [12, 13]

In order to design for a low MIPS outcome, one can either lower the material input necessary to provide a given service, or increase the number of services that can be completed during the lifetime of a product with a fixed number of resources. The former circumstance is simply designing to minimize material flows. Companies such as ZipCar exemplify the latter circumstance, as do hotels that ask patrons to use a towel for two days before requesting a new towel. [12, 13]

The MIPS of selected products and services are displayed in Table 4.3.1. The soil values are neglected because of inadequate data.

Material Info	Abiotic (kg/kg)	Biotic (kg/kg)	Water (kg/kg)	Air (kg/kg)
Aluminum	85	0	1380	9.8
Pig Iron	5.6	0	22	1
Steel (mix)	6.4	0	47	1.2
Copper	500	0	260	2
Concrete	1.3	0	3.4	0.04
Portland Cement	3.22	0	17	0.33
Plate-glass	2.9	0	12	0.74
Wood (Spruce)	0.68	4.7	9.4	0.16
Paper Clip	0.008	0	0.06	0.002
Shirt	1.6	0.6	400	0.06
Jeans	5.1	1.6	1200	0.15
Toilet Paper	0.3	0	3	0.13
Tooth Brush	0.12	0	1.5	0.028

Table 4.3.1: MIPS of various products and services [1]

Like the ecological rucksack, MIPS does not stand alone as an indicator of sustainability because the toxicity of materials is not incorporated in the metric. Another shortcoming of the metric is that it is very hard to calculate for a given service because there are so many hidden material flows. Because of the difficulty of calculating MIPS, one must often rely on MIPS values that have been extensively researched by industrial ecologists, and even then, they are only applicable to the specific region that they were calculated in, as manufacturing methods and electricity generation is different around the world. [12, 13]

The Wuppertal Institute in Germany has done extensive research and data collection to obtain MIPS values for many products and services. MIPS comparisons were generated using the Wuppertal values and the assumptions New Orleans housing addressed earlier. The comparison of MIPS of a Wood Stud, a Steel Frame, an AAC and a SIP house is displayed below for abiotic, biotic, water and air material inputs. [8, 9, 17]

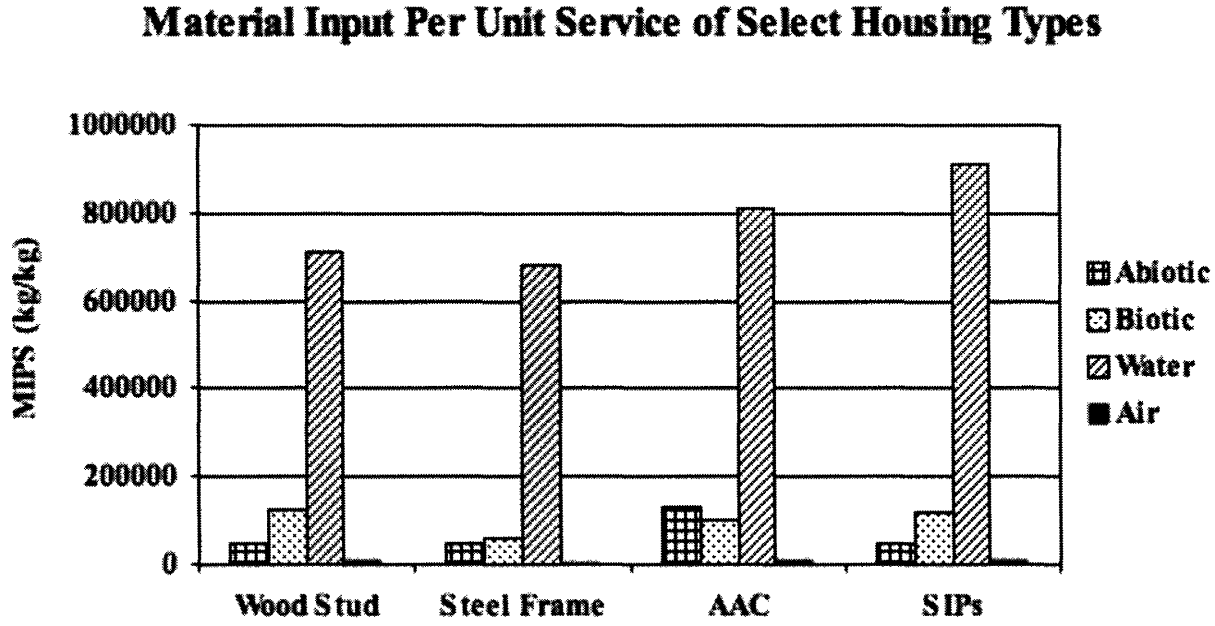

Figure 4.3.1: MIPS associated with selected housing types in New Orleans

Because the water values are much larger than the other material flows, a chart displaying only biotic and abiotic flows is shown in Figure 4.3.2. [8, 9, 17]

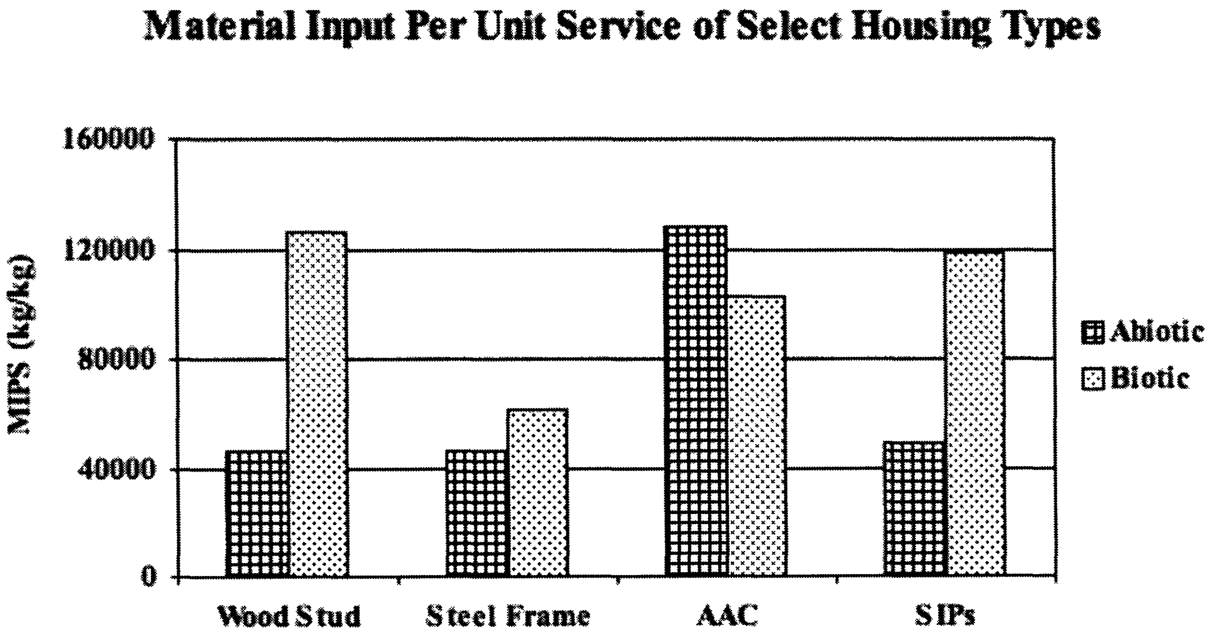

Figure 4.3.2: Abiotic and Biotic MIPS associated with selected housing types in New Orleans

The AAC house requires significantly more abiotic material to create one house, while the wood stud home requires the most biotic material simply because wood is a biotic material. It is interesting to note that the AAC house had the lowest ecological footprint, thus it seems that neither of these two indicators fully defines sustainability.

A chart depicting the total MIPS of these four housing types is displayed in Figure 4.3.3. [8, 9, 17]

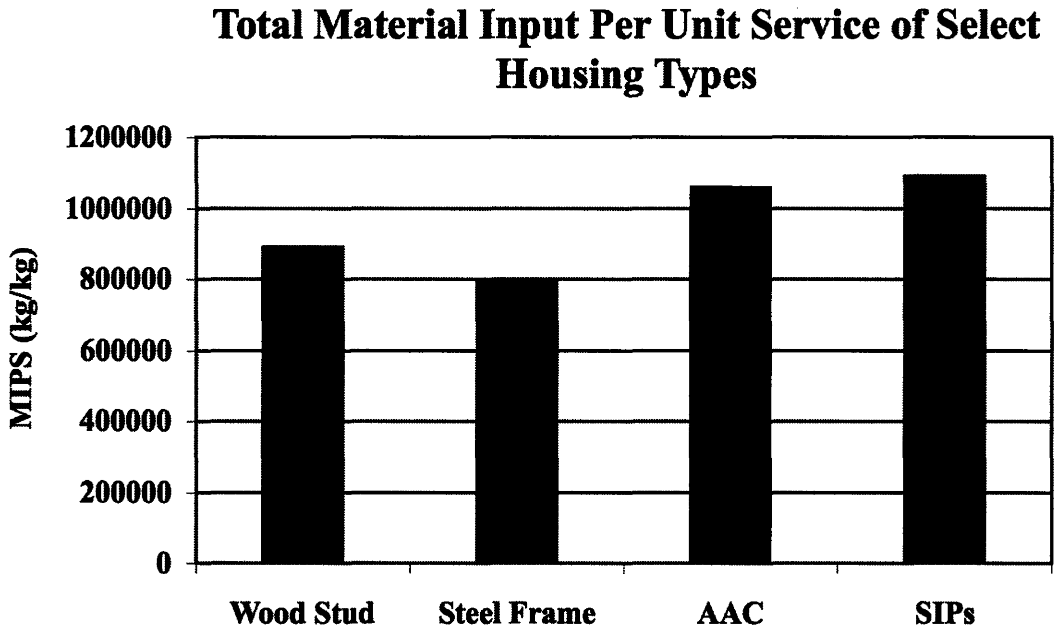

Figure 4.3.3: Total MIPS associated with selected housing types in New Orleans

Overall, the total MIPS values are relatively similar among the four housing types. As in the case of the ecological footprint, these calculations do not include the differences that would be apparent during the use phase of the houses, such as varying energy requirements. They do, however, include the energy required to transport the materials to the site and to construct the house.

4.4 Sustainability Process Index

Krotscheck and Narodoslawsky developed the sustainability process index or SPI in the late twentieth century as one of the most comprehensive measures of sustainability. It is similar to the ecological footprint in that SPI is measured in units of area, however it is process based, not agent based. It uses area because Krotscheck modeled the Earth as a system that is open to solar radiation, and he asserts that solar radiation is the only sustainable natural force for human and environmental processes, and this force is limited by the fact that the Earth is of a fixed surface area. Processes must compete against each other for the limited resource of area. [6]

The SPI metric is most often used to compare the sustainability of technological processes that achieve the same output. It allows engineers to evaluate technologies in a methodic way in order to achieve select the most sustainable process possible to complete a task. [1, 6]

The sustainability process calculation is displayed below:

$$A_{total} = A_R + A_E + A_I + A_S + A_P, \tag{10}$$

where A_R is the area necessary to produce raw materials, A_E is the area required to provide energy to for the process, A_I is the area attached to the physical installation or infrastructure of the process, A_S is the area required for staffing the process, and A_P is the area to allow for sustainable release of products and byproducts into the ecosphere. The A_{total} value is computed using mass and energy flows of the process for one year of operation. [6]

Like the ecological footprint, SPI assumes that each person deserves the same amount of area for his processes. According to Krotscheck and Narodoslawsky this value is about 80,000 m^2. Dividing the required for a process, such as one year of transportation, by the total area allowed for a given person, one gains the SPI value of that process as a percentage. If a transportation alternative can be found with a lower SPI, that unused area can be reallocated to another sector of the person's live, such as the process of acquiring food. [6]

The area required for raw materials is broken down in the following way:

$$A_R = A_{RR} + A_{FR} + A_{MR}, \tag{11}$$

where A_{RR} is the area that accounts for renewable resource, A_{FR} is the area that accounts for nonrenewable resources or fossil fuels, and A_{MR} is the area that accounts for minerals. [1, 6]

Because the SPI indicator considers the entire life cycle of a process, the energy required for playing and harvesting are the primary consideration in the calculations of biotic materials. For renewable resources

$$A_{RR} = \frac{F_R}{y_R}, \tag{12}$$

where y_R is the yield of a material [kg/m^2/year] and F_r is the feed of the process – how much material needed to fulfill service in question [kg/product]. The ecological rucksack of the material is included in F_r. [1, 6]

The calculation for nonrenewable raw materials is

$$A_{FR} = \frac{F_F}{y_F}, \tag{13}$$

where F_f is feed of fossil fuels and nonrenewable materials into the process [kg/process] including the rucksack and energy required for refining and transporting fossil fuels and y_f is the yield of sedimentation of carbon in the oceans [0.002 kg/m^2/year]. The yield value assumes that a process is sustainable if it emits less carbon than one can be sequestered via the ocean. [1, 6]

When calculating the minerals necessary for a process, one must consider the energy necessary to provide 1kg of the material to the process. This is expressed below:

$$A_{MR} = \frac{F_M E_D}{y_{EI}}, \tag{14}$$

where F_r is the flow of the raw mineral for the process [kg/process], y_{EI} is the energy yield for the energy [kWh/m^2/year] (takes into account the mix of energy used in the industry – electricity, heat or mechanical power), and E_D is the energy content per mass of raw material (including the energy required to supply 1kg of the material in question) [kWh/kg]. If t E_D is unknown it can be calculated as

$$E_D = \frac{C_N 0.95}{C_E}, \tag{15}$$

where C_N is the price of the material, and C_E is the price of one kWh of energy. Equation 15 uses the same assumption as Krotscheck and Narodoslawsky – energy consumption almost exclusively defines the price of raw materials. The area required for minerals can be combined with the area required for renewable and nonrenewable resources to get a total area value for resources. (Equation 11) [1, 6]

The area required to supply the energy for the process for a given year considers the specific energy carriers that are used in a region, such as coal or oil, to fulfill the needs of a process in its use phase. This calculation is similar to the one for raw materials, and can is displayed below:

$$A_E = \frac{F_E}{y_E}, \tag{16}$$

where F_E is the energy necessary for the process [kWh/process/year] and y_E is a yield specific to how the energy is generated [kWh/m^2]. Inverses of these values are displayed for selected energy sources in Table 4.4.1. Combining the values in the table with regional knowledge about a regions energy generation allows for a simple calculation of A_E. [1, 6]

Type of Energy	Energy Yields [m^2/kWh]
Coal-fired plant	316
Natural gas	126.7
Photovoltaic	63.8
Hydropower	11.7
Biomass	43.4
Fuel oil	193
Nuclear Power	531.7
Electricity (Austria)	152.3

Table 4.4.1: Energy yields for various modes of electricity generation [1, 6]

The area for installation is the direct land use required for the process. This includes the land required for any factories or roads used for transport. Because the same infrastructure is used for various processes, this value tends to be small and is neglected by much of the literature.

The area for staff is also usually neglected unless alternatives are being compared that require drastically different numbers of people per unit service.

The area for the dissipation of wastes and products is often a large part of the total area. This variable is calculated with the assumption that every process output will be dissipated into the environment, thus it is related to the environments rate of regeneration. [1, 6]

$$A_P = \frac{F_P}{R_C\, c_C}, \tag{17}$$

where FP is the mass per year of a given waste from the process (for example kg of cadmium per year) [kg/year], RC is the appropriate environmental renewal rate (for example kg soil/m^2/year) [kg/m2/year], and cc is the concentration of the element in the environmental compartment (for example kg of cadmium per kg of soil) [kg/kg]. For this variable, sustainability is achieved if the renewal rate of the environmental compartment (for example air, soil or water) outweighs the emissions of the process, thus leaving the composition of elements of the compartment unchanged. [1, 6]

The SPI is a more comprehensive metric than MIPS because it differentiates between the types of resource consumption (renewable versus nonrenewable), the emissions of the process and the waste. The major downfall of SPI is that it is very time intensive to find the appropriate regional data to perform a complete calculation. Unlike the Wuppertal Institute's study of MIPS, there are few databases with SPI information.

While it would be interesting to find the SPI comparisons for the four housing types in the systems model, the information necessary to perform such a calculation is not readily available. Once the model produces energy outputs for the use phase and deconstruction phases of the various housing types, these values can be combined with further research on New Orleans information such as fuel for electricity generation and forest yield factors, to calculate the SPI for the process of building, occupying and deconstructing the four housing types.

5.0 Conclusions and Further Work

Overall, composite indicators are must more effective in conveying the sustainability of material selection and construction processes for residential homes. Though a definitive choice cannot be made for which construction method is most sustainable for New Orleans, the concepts applied in this paper can be used in tandem with the systems model information to provide more complete comparisons. Future work may include finding regional information on embodied carbon and energy of various construction materials to update results with New Orleans specific values. Another interesting project would be to compare the four housing types using the SPI indicator for the life cycle of the house. If policy makers consider energy consumption and carbon dioxide emissions of the life cycle of a house when selecting preferred construction methods, these decisions will make New Orleans a more sustainable city and a model for twenty-first century urban metabolism.

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