RESEARCH TECHNICAL REPORT

The Influence of Risk Factors on Sustainable Development

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DISCLAIMER

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ABSTRACT

Efforts to date to assess carbon emissions from a facility have focused on normal operating conditions. In this work, a methodology is developed and applied that expands lifecycle carbon emissions to include the influence of risk factors due to fire and natural hazards. Both hazards are shown to present risk factors that are important potential sources of carbon emissions. Without effective fire protection systems, the risk of fire increases the carbon emissions by 30-40 kg of CO_2/m^2 (an increase of 1% -2 %) over the lifecycle of a standard office building, and can add up to 14% to the carbon emissions over the lifetime of a facility exposed to extensive fire hazards. Efforts to improve sustainability solely by increasing energy efficiency (without consideration of risk) have the potential to increase the relevance of risk factors by a factor of 3. Effective risk management through the use of automatic fire sprinkler systems reduces these lifecycle emissions to minimal levels. In areas exposed to natural hazards, such as wind hazards in the east and gulf coasts of the United States, risk from wind damage also increase the carbon emissions by 30-40 kg of CO_2/m^2 (an increase of 1% -2 %) over the lifecycle of a typical industrial building. These lifecycle emissions can be virtually eliminated by cost effective, robust, design and construction practices. Overall, the methodology and results presented herein illustrate the integral role of risk management in sustainable development.

INTRODUCTION

The construction, renovation or improvement of facilities is increasingly including measures to improve sustainability by reducing environmental impact over their operational lifecycle. Of primary environmental concern is the emission of greenhouse gases associated with the consumption of energy during normal operations, or required for the production and transportation of materials, and construction. Worldwide, 30-40% of all primary energy is used in buildings, with an even greater fraction of 40-45% of energy use within buildings in Europe [1].

Within the United States, the Leadership in Engineering and Environmental Design organization (LEED) has established metrics and certification levels for construction and renovation [2]. LEED certification checklists provide guidance for options and measures to reduce the environmental impact of facility construction and operations on carbon emissions. Certification by LEED provides a tangible measure of the sustainable posture of the facility.

Emphasis to date has appropriately focused on reduction in emissions related to energy consumption during operations, with a secondary emphasis on reducing embodied carbon emissions associated with the fabrication and transport of construction materials, and construction processes. In addition to these goals, critical objectives for environmental and developmental policies of sustainable development [3] include “reorienting technology and managing risk”. In this work, the emphasis on normal operations is supplemented with the analysis of potential risk factors that can affect the sustainability posture of a facility over its life cycle. The emphasis of this work is placed on large, industrial and commercial facilities that tend to have significant impact on society, both directly due to their contribution to the environment, as well as their economic impact to communities and company shareholders.

OBJECTIVE

The overall objective of this work is to provide the basis for improvements in risk management as an inherent part of sustainable development. This objective includes the development of a methodology for including risk management considerations in the lifecycle carbon emissions of a facility. This methodology is applied to fire and natural hazard risk factors in commercial and industrial facilities to provide quantitative estimates of possible carbon emission reductions and potential advancements in sustainable development resulting from improvements in risk management. The uniqueness of this work is due in part to a broader view of sustainable development, but also due to the characterization of frequency and severity of risk factors as provided by research in engineering sciences and loss data from commercial and industrial properties [4].

ANALYSIS

As a primary factor in sustainable development, the scope of this analysis will evaluate carbon emissions during operation and abnormal events over the overall lifecycle of a facility. The consumption of energy is considered implicitly by its contribution to carbon emissions using current energy production techniques. The advantages and additional risks posed by the use of alternative and more renewable energy sources remain for future consideration. In some cases, technologies to reduce energy consumption reduce risk, while in others the vulnerability of these systems to damage can increase the relevance of risk factors over their lifecycle.

The total carbon emission (TCE) over the lifecycle of a facility includes a sum of the emission from construction (including materials, transportation, and equipment usage), normal operation (primarily power consumption and utilities), maintenance and decommissioning (equipment usage for demolition, transportation for disposal) as given for example by Jones [5]:

$$TCE = CE_{const} + LCE_{oper} + LCE_{mnt} + CE_{decom} \qquad \text{Equation 1}$$

Carbon emissions from construction, CE_{const}, and decommissioning, CE_{decom}, are generally considered to be one time events. Emissions from maintenance, LCE_{mnt}, and operation, LCE_{oper}, are considered on an annual basis and included in the life cycle analysis by multiplying the annual rate of emission, ACE, by the years of service, LT, or life time of the building, for example as given for operations by

$$LCE_{oper} = LT * ACE_{oper}\,, \qquad \text{Equation 2}$$

where ACE_{oper} represents the annual rate of emission for operation and is typically referred to as the “carbon foot print”. Due to the primary importance of energy consumption on emissions associated with normal operations, annual rates of carbon emissions can readily be determined as outlined using standard guidance [6].

The emissions due to construction and decommissioning are typically referred to as embodied emissions given their inclusion in the physical facility rather than resulting from normal operations. Hence,

$$CE_{emb} = CE_{const} + CE_{decom} \qquad \text{Equation 3}$$

Select studies to date [7-11] have assessed total life cycle carbon emissions as well as the ratios of embodied to total carbon emissions for office and residential structures. Analysis of 10 office buildings by Suzuki and Oki in 1998 [7] built in Japan between 1976 and 1989 show average total carbon emissions of 4450 kg CO_2/ m^2 for a 40 year lifecycle with fractions of embodied to total carbon emissions of approximately 20%. The study included buildings with reinforced concrete, steel, and combined construction. Similar ratios of embodied carbon emissions, as well as additional environmental impacts of summer smog, acidification, eutrophication and heavy metals are noted in the 2004 study by Junnila in Finland [8]. For a 50 year lifecycle, data from an intermediate sized office building (4400m^2) in Finland show carbon emissions of 3300 kg CO_2/ m^2, with embodied energy representing 15-20% of the total. Similar proportions were determined in the same study for a comparable size commercial building located in the Midwest region of the United States. For comparison, residential properties in the UK [9] have a lower 50 year lifecycle emission of approximately 1700 kg/m^2. Studies on commercial buildings in Vancouver and Toronto by Cole and Kernan in 1996 [10] also provide results of 12% to 20% embodied energy, with lesser amounts associated with construction including significant amounts of wood as shown by Buchanan and Honey [11].

With the largest fraction of the life cycle carbon emission occurring during operation of a facility, efforts to promote energy savings will provide significant overall reductions. As these reductions in operating emissions occurs, it is important to assess factors resulting from the risk of abnormal events such as fire, flood, or wind damage that affect the life cycle sustainability of the building.

The comprehensive life cycle carbon emissions, *LCE*, should therefore be given by

$$LCE = TCE + LCE_{risk} \text{ ,} \qquad \text{Equation 4}$$

where LCE_{risk} represents carbon emissions associated with risk factors over the lifetime of the building. To assess the relevance of risk events to overall carbon emissions of a building, this analysis uses a risk fraction (*RF*) to express the ratio of emissions due to risk factors to the total carbon emission over the building lifecycle as given by the following relationship:

$$RF = LCE_{risk} / TCE \qquad \text{Equation 5}$$

The risk fraction therefore represents the increase that risk factors pose to the sustainability posture of a facility over its lifetime. With assessment, appropriate and cost effective risk management practices can be selected to minimize risk and hence reduce the associated emissions. These risk management practices have complementary benefit of improving business continuity and enhancing life safety that generally make them wise decisions, in addition to the sustainability contribution highlighted in this analysis.

Analysis of Fire Risk

For a non-manufacturing facility located in an area without significant exposure to natural hazards (such as wind, earthquake or flood damage), property loss history indicates that property risks are dominated by fire hazards. Fires are themselves a significant and visible source of direct emission (including carbon dioxide and carbonaceous soot) as well as a source of indirect emissions due to loss of property and release of embodied emissions. The carbon emission risk fraction posed by fire hazards is expressed by

$$RF = f_f * LT * \left(\frac{F_b * m_f * e_{CO_2}}{TCE} + \frac{F_r * CE_{emb}}{TCE} \right) \qquad \text{Equation 6}$$

Where,

f_f = *annual frequency, fires/year*

F_b = *Fraction of material burned*

m_f = *Combustible material (i.e. fuel) density, kg fuel/*m^2

e_{CO2} = *CO_2 released per unit material burned, kg CO_2/kg fuel*

TCE = *Total Lifecycle CO_2 emissions per unit area, kg CO_2/m^2*

F_r = *Fraction of material to be replaced during reconstruction*

CE_{emb}= *Total Embodied CO_2 emissions per unit area, kg CO_2/m^2*

Note that the risk fraction results from Equation 6 are independent of total size of the building and expressed on a per unit floor area basis. Variations with building height are neglected. The first term represents the emission from the fire, with a fraction of the total material burned expressed by F_b. As the level of combustible material used in construction, contents and furnishings increases, F_b will increase towards an upper bound of unity. The second term represents the release and replacement of the embodied carbon emissions that occurs during reconstruction of the fraction of the structure due to material damage (i.e. F_r) by the fire as well as by smoke or water. Disposal of damaged material would also be included in reconstruction, but no studies to date have quantified these values.

Note that although F_b has an upper value of 1.0, F_r may exceed 1.0 since carbon emissions due to disposal and reconstruction will exceed the embodied carbon associated with a green field site. It should be noted that energy used for transportation and operations of workers and equipment, as well as on site energy use as evaluated by Cole for different construction assemblies [12], have all been included as part of the embodied carbon emissions. Emissions due to maintenance have been neglected, since numerous studies [7, 8, 13] show minimal contribution to life cycle emissions. Furthermore, upkeep of surroundings, such as landscaping, is beyond the scope of this study on structures.

The risk fraction, as well as the two individual terms, in Equation 6 is illustrated graphically in Figure 1. Time periods for construction, rebuilding and demolition are not to scale and have been expanded to enhance readability.

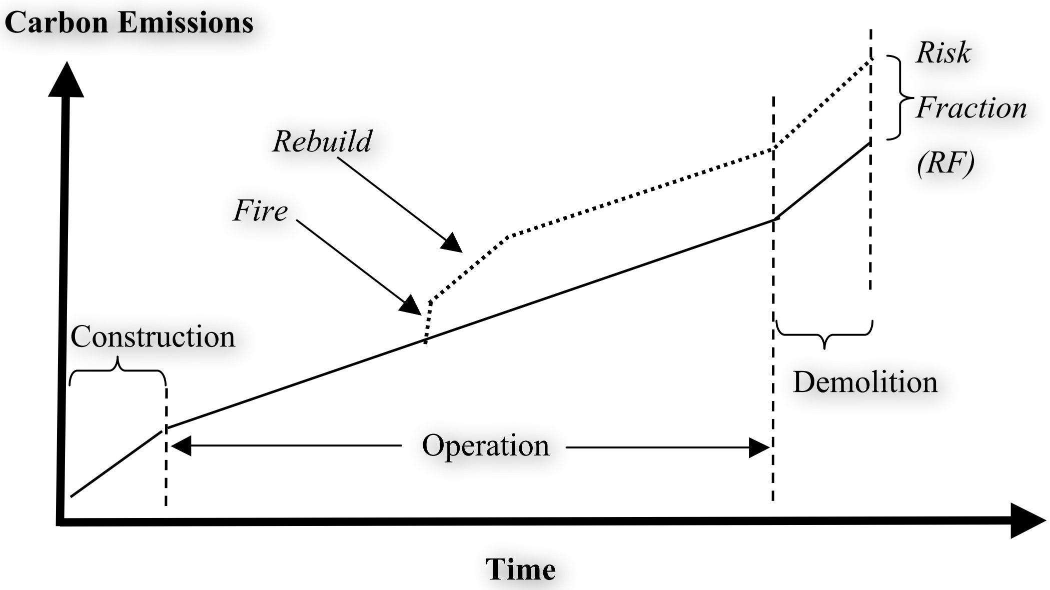

Figure 1: Conceptual Diagram of Contribution of Risk Factors for Lifecycle Carbon Emissions

A reduction in the risk fraction can be achieved through effective risk management strategies which can serve to reduce the fire frequency (such as hot work processes that reduce ignition of combustible materials) and/or serve to reduce the extent of damage produced and reconstruction required. Automatic fire sprinklers (AFS) are the most common and cost effective method to reduce both the frequency of large fires, and the severity of damage (and hence the fraction required for reconstruction). Fire frequency data implicitly include some minimum threshold for fire size, since very small or incipient fires cause minimal damage and are frequently extinguished without record. Furthermore, fire severity data are often expressed in terms of loss values, which may or may not include full cost of replacement. Given the challenges inherent in partitioning the potential benefit of risk reduction from AFS to reduction in frequency, reduction in fraction burned, and/or reduction in replacement, the approach taken in this study is to conservatively assume the replacement fraction is equal to the burned fraction (i.e. $F_r = F_b$). For this case, the risk fraction is reduced by a factor equal to the reduction in overall damage provided by automatic fire sprinklers, F_{AFS}, as given by

$$F_{AFS} = \left[f_f * F_b\right] / \left[f_f * F_b\right]_{AFS}, \text{ and } RF_{AFS} = RF_{fire} / F_{AFS}, \qquad \text{Equation 7}$$

where the *AFS* subscript denotes the values for reduced fire frequency and reduced burned fraction, respectively, inside the braces.

Three examples are provided in Table 1 to illustrate the influence of fire risk on life cycle carbon emissions. Examples include a current standard office building, an office building with reduced operating emissions motivated by sustainability concerns, and a facility exposed to greater fire hazards such as an industrial or light manufacturing plant.

Table 1. Lifecycle Carbon Emissions due to Fire Risk for Large (>$1M) Fires.

Symbol	**Parameter, units**	**Case 1: Current Standard Office Building**	**Case 2: Office Building, Reduced Operating Emissions**	**Case 3: High Hazard Facility**	**Ref.**
f_f	*Frequency of large fires, fires/yr*	*0.001*	*0.001*	*0.016*	*[4]*
LT	*Lifetime, yrs*	*40-60*	*50*	*40*	*[5],[7], [10]*
m_f	*Fuel density, kg/m*^{2}	*38-115*	*110 (est)*	*40 (est)*	*[14]*
e_{CO2}	CO_2 *per unit mass burned*	*3.0*	*3.0*	*3.0*	*[15]*
TCE	*Total lifecycle carbon emissions, kg* CO_2/m^2	*3300-4500*	*2000*	*4000 (est)*	*[7], [8], [10]*
F_{emb}	*Embodied fraction of total carbon emissions*	*0.15-0.2*	*0.6*	*0.2*	*[7], [8], [10]*
F_b	*Fraction burned, no AFS*	*0.5-0.8*	*0.7-1.0*	*0.7(est)*	*[4]*
F_r	*Fraction replaced, no AFS*	*0.8-1.0*	*1.0*	*1.0 (est)*	*[4]*
F_{AFS}	*Reduction in Property Loss achieved by AFS*	*30-40*	*30-40*	*30-40*	*[16], [17]*
Results					
RF_{fire}	*Fraction of Total Carbon Emissions due to Fire Risk, no active protection*	***1 – 2***	***4***	***14***	*Eqn. 6*
$RF_{fire,\ AFS}$	*Fraction of Total Carbon Emissions due to Fire Risk, with AFS, %*	***< 0.1***	***0.1***	***0.4***	*Eqn. 7*

The key parameters for this study are based on values in the literature and nominal commercial/industrial property for which sufficient data exist in the FM Global Property Loss database [4]. References are provided for each value, and estimates (where necessary due to lack of data) are noted. Where possible, a range of values are presented to reflect variability. It should be emphasized that these are nominal values to provide an assessment of the relative contribution of risk factors. Individual contributions will vary strongly by location, design, construction, and operations.

Of the three cases presented, the first provides a baseline using a current standard office building, and provides reference for discussion of the individual parameters and their sources. The fire frequency represents the probability of large (over 1$mil USD) loss fires for a facility without adequate risk management measures, which in this case is commonly accepted to be an adequate automatic fire sprinkler system. Within this class of events, the burned fraction and replacement fraction are expected to be significant.

For the purpose of lifecycle analysis, investigators have used a range of different lifetimes to perform previous studies. Typical lifetimes are 40-60 years, with values up to 100 years in limited cases referenced by Sartori and Hestnes [13]. Since both lifecycle carbon emission and fraction of embodied carbon are directly dependant on the lifetime, corresponding values for each must be used in Equation 6. The ranges of lifetimes and embodied carbon ratios (equal to CE_{emb}/TCE) presented in Table 1 reflect variation of values provided in the referenced literature.

Fuel density values provided in Table 1 are from the National Fire Protection Association (NFPA) handbook [14]. General use occupied space typically contains approximately 38 kg/m^2 of combustible material, where as areas with dense storage, such as libraries, can result in increased nominal loads of 115 kg/m^2. Note that these fuel loads include “contents, interior finish, floor finish and structural elements”. Typical analysis of embodied carbon is focused on building materials and does not include contents and furnishings. Since these items will frequently be consumed by the fire and replaced, actual values of the embodied carbon and replacement fraction will be greater than values currently cited in the literature.

The CO_2 emitted per unit mass burned is based on combustion analysis and flammability data from Tewarson [15]. Values for total carbon emissions and embodied fraction are from references [7,8, 10] as discussed in the previous section.

The consideration of large fires reflected in the fire frequency is also represented in the range of values for the fraction of combustibles burned and the fraction of the embodied carbon that requires replacement. Large fire events considered here result in major degrees of damage which typically require extensive (i.e. over 50%) replacement of materials. Accordingly, values of burned fraction, (F_b) varying from 0.5 to 0.8 as well as the replacement fractions (F_r) varying from 0.8 to 1.0 are included in Table 1. Although large fires are less frequent than less severe fires, they pose the greater threat to the sustainability posture of a facility over its life time. Small fires are also less frequently reported and, in unprotected structures, often become large fires.

Case 2 and 3 are hypothetical cases based on the two main variations of a highly sustainable low hazard (i.e. office or hotel) facility, and a light manufacturing or material working facility. Case 2 is motivated by lifecycle analyses performed for residences and office buildings as recently reviewed by Sartori and Hestnes [13] as well as the impact of sustainable construction trends noted by Cole and Kernan [10]. Both note that materials and designs for sustainable development are duly focused on reducing emission associated with operations. As reductions in operating, and therefore overall, emissions are achieved by more energy efficient designs and materials, not only will the relative fraction of embodied carbon emission increase, but the absolute value of embodied carbon emission will increase as more material and process intensive components are used to achieve energy efficiency. Using energy consumption to represent carbon emissions, Cole and Kernan note that, as operating energy is reduced to 50% below 1996 standards, embodied energy will dominate life cycle emissions resulting in ratios of embodied to total lifecycle carbon emissions in the range of 55-65%. Values for case 2 are generally taken from Cole and Kernan. In cases where data are not available, estimates are based on the assumption that design and construction is driven solely by energy efficiency and renewable material objectives, resulting in greater fuel densities and more combustible building materials. This trend is shown conceptually in Figure 2.

The final case represents a light manufacturing facility, where loss data [4] illustrates that the presence of ignition sources as well as combustible and/or flammable materials results in a significantly greater frequency of large fires. Such facilities include activities such as metal working, machine operations, or small item manufacturing. Fuel loads will vary widely, and due to lack of data, are estimated to be slightly less than standard office buildings due to the lack of furnishings, decorative wall linings, and contents. Total lifecycle carbon emissions for this class of facilities were not found in the available literature and hence estimated to approach the upper bound for a standard office building with balancing factors of increased energy usage for equipment, and reduced heating and cooling requirements. Unprotected fires in these structures tend to be severe, often resulting in extensive damage and complete reconstruction, hence burned and replacement fractions of 0.7 and 1.0 were estimated based on historical data [4].

The reduction in fire risk provided by automatic fire sprinklers will vary across occupancies and construction type. Results cited by Munich Re [16] from analysis of 17 electrical industry risks in Germany covering over 3.7 million square meters show losses were reduced by a factor of 36 when AFS systems were installed. FM Global detailed loss statistics [17] show a reduction of a factor of 4-5 in fire severity, and loss data for light hazard occupancies show a corresponding order of magnitude reduction in fire frequency for large (over 1$M) fire losses with well designed and maintained fire sprinkler systems. Data therefore indicate that a range of 30-40 reduction in risk of emissions from large fire losses is possible and hence reflected in Table 1.

Fire Hazard Results

The results shown in Table 1 illustrate that risk factors increase the lifecycle carbon emissions of a standard office building on the order of 1-2%. Uncertainty and variability of parameters, combined with conservative assumptions of fire frequency, lack of accounting for emissions due to disposal, and the influence of furnishings on the embodied emission, provide results with single significant figure accuracy. Hence, the presence of fire risk results in an increase of on the order of 30-40 kg of CO_2 for each square meter of space in a standard office building.

Modest estimates of reductions in risk achieved by automatic fire sprinkler systems reduces the risk contribution to lifecycle emissions by an order of magnitude to less than 0.1%, and 3-4 kg of

CO_2 for each square meter of space. To achieve this reduction in emissions, automatic fire sprinkler system design practices for highly protected risks [18] require the addition of nominally 2.0 kg/m^2 of steel to the building. Using upper bound values determined by Buchanan and Honey [11] for embodied carbon emissions associated with steel pipe produced using only fossil fuels, the steel required for an automatic fire sprinkler system adds negligible carbon emissions of 4.0 kg CO_2/m^2 to the building. Risk management of fire hazards due to the installation of sprinkler systems therefore produces an approximate net gain on the order of 30-40 kg of CO_2 for each square meter of space in a standard office building. Hence, fire risk factors play a measurable role in the sustainability of even a standard, low hazard office building and therefore risk management for loss prevention should be considered as part of sustainable design.

It should be noted that secondary factors for carbon emissions associated with risk management are more difficult to quantify and can be expected to be much less that the primary risk fraction given in Equation 6. For example, small amounts of carbon emissions are associated with periodic maintenance and testing of fire protection systems. Favorable secondary emission factors associated with good risk management of fire hazards include the reduction in carbon emissions associated with necessary infrastructure for life safety, such as roads and fire hydrants, as well as emissions due to equipment and energy consumed during fire fighting and emergency response. The environmental benefit of reduced water may be of greater importance, but is beyond the scope of this study.

For Case 2, the standard office building with an improved sustainability posture achieved by reducing operating emissions, the influence of risk factors increases to nominally 4% over the lifetime of the facility. Although the contribution of 1-2% for existing structures is worthy of reduction, the importance of risk factors will gain increased significance as future efforts progress to reduce the carbon footprint of operating facilities. As shown conceptually in Figure 2, the impact of a fire in a more “sustainable” building without consideration of risk factors and the need for risk management can result in lifetime carbon emissions that are greater than if sustainability had never been considered in the design. As was shown in case 1, the use of automatic fire sprinkler systems provides an order of magnitude reduction in the risk factor contribution to lifecycle emissions. Accordingly, sustainable design must be such that risks are considered and managed to avoid unintended consequences that actually cause greater emissions.

Case 3 presents a bounding case that highlights the importance of fire frequency on risk factors for occupancies housing activities with a higher propensity for fire hazards. Due to the linear relationship of frequency and risk factors in Equation 6, the risk of large fires in light manufacturing facilities with greater fire risk results in a 14% increase in lifecycle carbon emissions. Using standard data for the reduction in fire property loss resulting from automatic fire sprinkler systems, the contribution of risk factors provided by Equation 6 are reduced to 0.4% to 3%. Deployment of existing loss prevention measures that are tailored for the inherent hazards of specific activities will provide even greater loss prevention effectiveness, potentially driving contribution of risk factors down to the negligible levels achieved by risk management in well-protected standard offices and future sustainable designs.

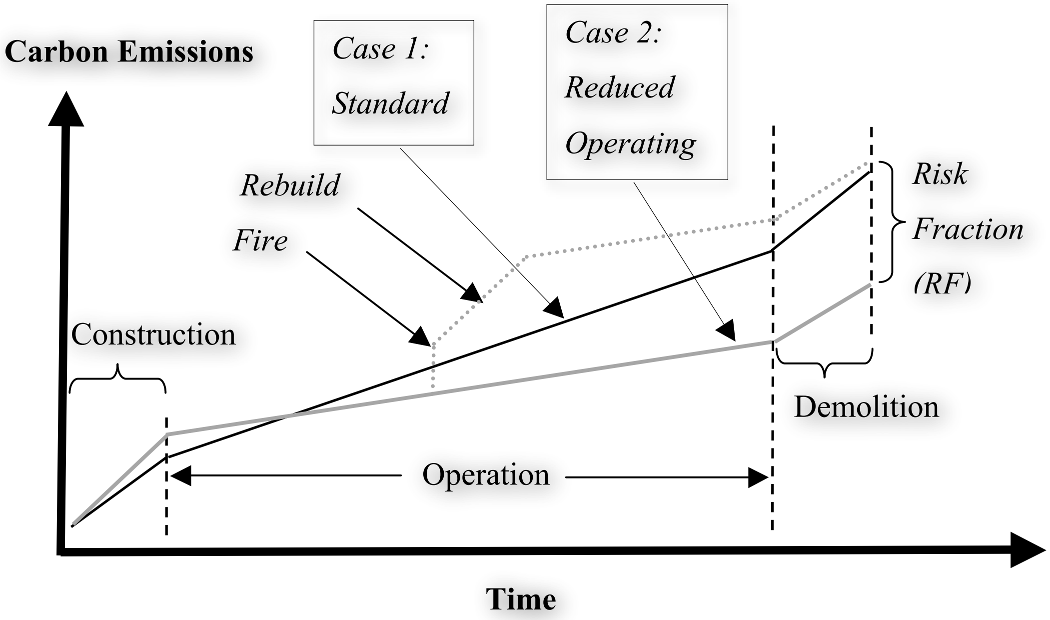

Figure 2: Conceptual Diagram of the Impact of Sustainable Designs with Reduced Operating Emissions.

Natural Hazard Risk

For natural hazards, the relationship expressing the contribution of risk factors to lifecycle carbon emissions is simplified by the elimination of the prompt carbon emission due to burning.

When written in terms of the return period of the hazard in years (as commonly applied in natural hazards assessment), RP_{nh}, the risk fraction is given by;

$$RF = \frac{LT * F_r * F_{emb}}{RP_{nh}} \qquad \text{Equation 8}$$

Although Equation 8 applies for any natural hazard, wind storms will be used here as an illustrative example. Winds due to hurricanes pose a significant risk along the southeast coast and Gulf of Mexico in the United States, and typhoons affect significant areas of eastern Asia. Additional hazards from earthquakes and floods can also be evaluated using an analogous approach, however the frequency and severity of these hazards tend to vary strongly by location.

For example, consider construction typical of an industrial facility and an office building located in Miami, Florida along the southeastern coast of the United States and hence exposed to hurricane hazards. Key parameters are provided for these two cases in Table 2. For wind hazards, the replacement fraction can be estimated based on the damage produced by wind speeds associated with the return period of the storm. Design wind speed values for a 3-second peak gust are given for 50, 100 and 500 year exceedance return periods by Vickery [19]. Similar wind maps are available in American Society of Civil Engineers Standard ASCE 7 [20]. Values in Table 2 are for the Miami area. Similar wind hazard data are available worldwide and form the basis for many building codes.

Commercially available catastrophe exposure models use damage functions to assess the vulnerability of structures to forces as a function of wind speed. For this study, both buildings are modeled as braced steel frame structures. The office occupancy is represented by a 22 m five story tall building and the industrial building is a 10 m single story structure.

In Table 2, the replacement fraction is conservatively estimated to be equal to 125% of the mean damage fraction predicted by the RMS Risklink model [21]. The fraction of material actually replaced during reconstruction will likely far exceed an additional 25% beyond the damaged fraction due to secondary damage and construction practices. Note that neither content damage, nor water damage from precipitation, has been included in this analysis. Both of these factors, which are highly variable and difficult to quantify in general, will increase the carbon emissions associated with disposal and replacement.

Wind Hazard Results

The results shown in Table 2 consider facility lifetimes of 50 years and embodied carbon emissions of 20%, from Suzuki and Oki [7]. Risk fraction values illustrate a typical increase of carbon emissions due to wind exposure in the range of 1% or slightly greater. Analyses were also performed for structures located in the Houston, Texas area, along the Gulf of Mexico, with similar results. Hence, the risk of wind damage results in a comparable increase in carbon emission over the lifecycle as fire risk poses to a standard office building. Although slightly greater values are observed for the industrial structure, risk fractions are in the same range for both types of buildings. As expected, the results show a slightly larger impact of more severe winds over the building lifetime, despite the increase in return period with increasing wind speeds and the linear dependence of the risk fraction on the return period of the event given by Equation 8. The results presented in Table 2 show an average increase in carbon emissions over the lifecycle of a structure in a wind prone region is on the order of 30-40 kg of CO_2 for each square meter of space. Damage to, and replacement of, contents will increase these emissions.

Table 2. Lifecycle Carbon Emissions due to Wind Hazard Risk, Southeast United States

Wind Hazard Data		Industrial Building		Office Building	
Return Period (RP), years	Wind Speed, mph	Replacement Fraction (F_r), %	Risk Fraction (RF), %	Replacement Fraction (F_r), %	Risk Fraction (RF), %
50	125	4	**0.8**	1	**0.2**
100	145	13	**1.3**	5	**0.5**
500	180	64	**1.3**	44	**1**

Risk management practices are also available [22] for wind hazards that effectively eliminate the contribution of risk factors to lifecycle emissions. These improvements are primarily related to robust roof designs, materials and construction. Recent property damage data from the extensive series of storms in the United States in 2004 and 2005 illustrate the effectiveness of reducing life cycle carbon emissions, as well as demonstrate the business value and return on investment of achieving highly protected risk status for commercial and industrial properties. For hurricane Katrina in the Gulf of Mexico, locations that met standards for highly protected risk, as provided in [22], experienced a factor of 6 less property damage related losses [4]. Similarly, damage was reduced by a factor of 4 for hurricane Rita in southern Florida [4]. Most risk improvement measures required to achieve this reduction in damage cost less than $10,000 to implement.

In the case of these large scale catastrophes, increase in carbon emissions due to risk factors are perhaps more pronounced than a single fire event since the ability to quickly and easily dispose of damaged material, transport new material, and rebuild is significantly reduced due the large number of affected buildings and damage to infrastructure and support services. Increased usage of energy from temporary power also increases emissions. Furthermore, unlike fire damage, the volume of the construction material is not reduced by the event thereby increasing the emissions associated with transportation and disposal. These and other secondary factors are difficult to quantify and will vary strongly based on the location and severity of the event.

CONCLUSIONS

Previous work on sustainable design has appropriately focused on energy efficiency as the main source of carbon related emissions. In this study, consideration is expanded to consider the influence of risk factors. Although these factors may include any potential hazard to the building or facility, the most relevant are due to fire and natural hazards. Using the method presented herein, analysis of the nominal contribution of these risk factors to the lifecycle carbon emissions of a facility provides the following conclusions:

- The risk of fire increases the carbon emissions of a standard office building by 30-40 kg of CO_2/m^2 over the building lifecycle, a total increase of 1% -2 %.
- Fire risk factors can add up to 14% to the carbon emissions over the lifetime of a facility exposed to extensive fire hazards.
- Future efforts to improve sustainability by improving energy efficiency have the potential to increase the contribution of fire risk factors to sustainable design by a factor of 3.
- As an example of natural hazards, in areas with wind hazards (such as the East and Gulf coasts of the United States) risk from wind damage increase the carbon emissions over the lifecycle of a building by approximately 1%.
- Available loss prevention measures, implemented as part of an effective risk management practices, can reduce the increase in carbon emissions to negligible levels.
    - Fire risk factors can be effectively addressed by the addition of automatic fire sprinkler systems.
    - Wind risk factors can be addressed through robust roof design and construction.

The results illustrate that risk management is inherent in achieving sustainability due to the contribution of risk to potential emissions. In the future, risk management will gain increased importance as advances in sustainable designs that do not consider risk factors have the potential for unintended consequences with even greater emissions. It is therefore recommended that future criteria for sustainable design and operation consider the contribution of risk factors and hence the importance of risk management as an integral part of sustainable development.

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