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Development of a multi-objective optimization tool for selecting thermal insulation materials in sustainable designs

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ABSTRACT

A multi-objective fire safety and sustainability screening tool for specifying insulation materials has been developed. This paper discusses a methodology for balancing competing requirements by evaluating the thermal resistance, fire performance, sustainability, cost, acoustic damping, and durability objectives of various insulating materials through implementation of a weighted mean. Each variable is normalized and then weighted according to the emphasis placed on each objective, using experimental data for the relevant material property. Two control scenarios and four weighting scenarios are presented. The first control scenario excludes both the fire performance and sustainability objectives in the material evaluations. The second control scenario introduces sustainability as an objective, but still excludes fire performance. The four weighting scenarios each emphasize a different area of consideration: cost, thermal resistance, sustainability, or fire performance. Materials considered are cellulose, fiberglass, rockwool, polyurethane, and polystyrene. Results of this analysis rank the materials in order of desirability and provide a method to reorder this ranking based on the priority assigned to each objective. For the four weighting scenarios presented, rockwool was consistently ranked as the best performer, while extruded polystyrene was typically the weakest. However, in the first control scenario, closed-cell polyurethane performed best and cellulose performed worst.

1. Introduction

Modern building design considerations frequently include reduced environmental impact through efficient energy, water, and material use. Sustainable designers may also seek to optimize the indoor environmental quality (IEQ), the site and space, as well as the operations and maintenance of the building. New types of materials and features have been developed to address these priorities, because these new elements help to attain lower life cycle energy and environmental costs for the site. Several of these elements have garnered attention from the fire safety community due to the uncertainty of their performance in a fire event [1].

1.1. Sustainability and fire

Although the choice of materials and elements for sustainable design does not focus on performance during a fire, it is possible that a single fire event can negate several, if not all, elements of green design. Environmental consequences of a fire include toxic smoke, greenhouse gas (GHG) emissions, water consumption to control the fire, wastewater runoff, solid waste disposal in landfills, and carbon costs in damaged material replacement. It has been shown that a building's life cycle carbon dioxide (CO_2) emissions can increase between 2% to 14% if a fire and subsequent rebuild occurs (Fig. 1). Further, without risk consideration during sustainability improvements, the contribution of fire risk to the total life cycle carbon emissions of a building can increase as much as threefold [2]. On average, a single residential fire emits GHGs equivalent to 250 kg of carbon dioxide (CO_{2e}) [3], which, for comparison, is equal to the total emissions from a 1000 km (620 mile) trip in a passenger vehicle [4]. Approximately 400,000 residential fires occur annually in the United States [5]. In addition to emissions concerns, firefighting is a water intensive process, requiring 138 L/m^2 (3.4 gal/ft^2) of water per affected room area [3]. Worse still, firefighting wastewater can easily exceed environmental standards, causing ecological damage that can last years [3].

Despite the inherent environmental damage of fire, this risk is not traditionally considered a factor in sustainable design by certification agencies, policymakers, or researchers. Standard life cycle assessments (LCA), which quantify the cradle-to-grave environmental impact of a product or system, do not incorporate risk

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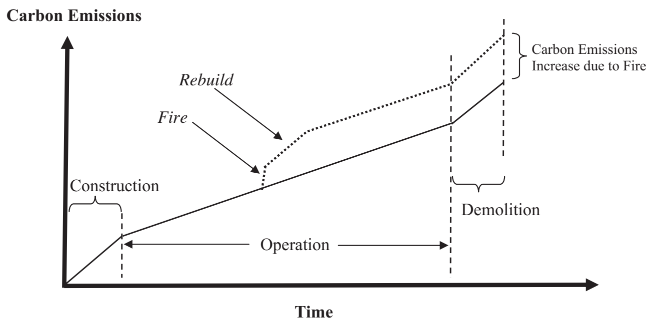

Fig. 1. Courtesy of FM Global. Impact on a building's life cycle carbon emission due to risk factors. Not to scale. The solid line indicates carbon emissions under normal conditions; the dashed line is the increase due to a fire event [3].

assessment (e.g. environmental harm of a building fire) [6]. In contrast, addition of fire risk assessment in LCA of a product with flame retardant (FR) chemicals can illustrate the increased environmental impact when weighed against statistical risk [6]. In this way, LCA, incorporated with statistical risk, can help reduce overall environmental impact while keeping safety in mind.

Furthermore, there are currently no Leadership in Energy and Environmental Design (LEED) credits for fire safety or fire protection as a component of sustainability. LEED is the leading green building certification program in the United States, and was developed by the US Green Building Council. Although fire safety is not acknowledged, there are several LEED credit categories for which it is relevant, namely

- *Water Efficiency*: points awarded for methods of reducing consumption
- *Sustainable Sites*: points awarded for minimizing impact to the local ecosystems and water resources
- *Green Infrastructure and Buildings*: points awarded for reducing the consequences of construction and operation of the site

Ultimately, the negative impact fire can have on sustainable design has not been fully recognized. Although there might be several objectives to balance during the design process, in many cases precautions taken for fire can improve both the safety and sustainability of the building. Prevention and management of fire is possible if, during the design process, steps are taken to ensure both fire safe and sustainable construction.

1.2. Selection choice and goals

Insulating material is ubiquitous to built structures. These materials reduce the thermal load of the building, thus reducing the energy consumption needed to control the climate of the indoor environment. Through this function, insulation is a prominent feature of all sustainable buildings. In fact, several LEED credit categories are applicable to insulation, which go beyond just its thermal properties

- *Energy and Atmosphere*: points awarded for building energy performance
- *Materials and Resources*: points awarded for sustainable material use and reduction of waste
- *Indoor Environmental Quality*: points awarded for improved indoor air quality (IAQ), lighting, etc.
- *Innovation in Design*: points may be awarded for unusual features that meet any sustainability goal

Although thermal insulation is a necessary component of building design, multiple fire incidents have occurred where insulation was a major contributor to the spread and intensity of the fire event. The subsequent section relates two example cases. Because of the aforementioned factors, insulation was selected as the building component for demonstrating the selection tool that was developed for this work. The task of choosing the proper insulation is not as straightforward as one might imagine, and several attributes must be weighed to optimize the selection. This paper aims to offer such an optimization tool, by selecting a sample of commercially available insulation and ranking each on a relative scale. In short, this paper will identify objectives that might be of importance to building designers or regulators; obtain attribute data from literature for each objective that is relevant and quantifiable; develop a multi-objective optimization (MOO) methodology for evaluation of insulating materials, relative to one another; present example weighting scenarios and rank the insulating materials.

1.3. Concealed space fires

Insulation may be installed in attics or roofs or in concealed spaces, such as wall or floor cavities. Combustible material is allowed in such spaces, provided sufficient protection from a thermal barrier (such as gypsum board) is present. Evidence suggests that insulation, regardless of material, will not contribute significantly to flame spread if the concealed space is sealed, fire blocks are properly installed, and the air gap is less than 25 mm within the cavity [7]. As air availability within the cavity is the key component in allowing significant flame propagation, contact between the insulation and the thermal barrier is recommended. Fire blocks, spaced effectively to disallow large continuous areas of insulation, additionally act as a mechanism to prevent flame spread, if oxygen is sufficient. Variations and ambiguity in local code requirements can ultimately result in the neglect of either or both of these two installation techniques [8]. If these fire mitigation methods are employed, but proper installation is not performed, or later alterations to the building or aging of the building create such a situation as to allow increased ventilation, material flammability becomes more important. Although, in theory, these installation techniques make the combustibility of insulation moot, in practice it is unlikely that these methods can be completely effective, due either to irregularities during installation or alterations to the building later on. For example, the appropriate fire block technique was employed in the construction of a vegetable processing building in Yuma, Arizona, which was insulated with plastic foam. In 1992, despite the blocks, fire spread uninhibited throughout the concealed spaces, causing irreparable harm [8]. Annually, about 16,600 (5%) of reported home structure fires in the U.S. originate within attic/ceiling/roof assemblies or walls and other concealed spaces. These types of fires result in 2% (50) of the civilian fire deaths, 2% (260) of the civilian fire injuries, and account for 10% ($740 million) of the direct property fire damage to home structures. Contribution of concealed spaces to fire spread is not as easily quantified, as classification of fires not originating in a room is difficult [9]. The extent to which attics and concealed spaces affect other types of structures (such as high rises or commercial buildings) in fire is unknown. Anecdotally, contents of concealed spaces can have a major impact on fire. In 2013, a fire occurred at the Organic Valley dairy cooperative headquarters in Wisconsin. The fire was believed to have originated within the wall cavity, and progressed throughout the building via the concealed space. Again, the installed fire blocks had little, if any effect, on impeding the fire spread. Additionally, the building was equipped with sprinklers, but sprinkler extinction was impossible because of the fire's location in the concealed spaces inside the walls. Ultimately, the fire was able to spread for 18 h, despite firefighting efforts, causing $13 million in property damage and other losses (the building cost $5.9 million to build in 2004). The extent of damage was in no small part due to the combustion of the insulation