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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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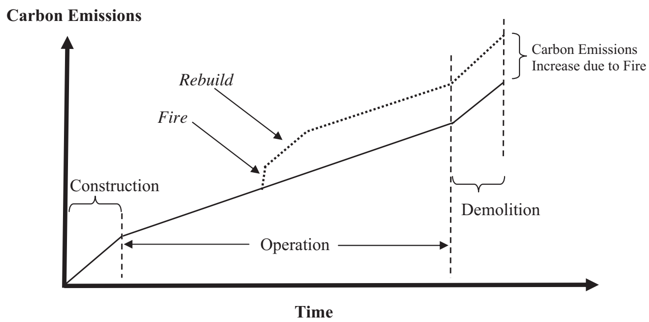

Fig. 1. Courtesy of FM Global. Impact on a building's life cycle carbon emission due to risk factors. Not to scale. The solid line indicates carbon emissions under normal conditions; the dashed line is the increase due to a fire event [3].

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

Table 1
Insulation material nominal densities and thicknesses from the manufacturer's product specifications.

Material	Abbrv.	ρ [kg/m^3]	δ [mm]
Conventional Fiberglass	FG-C	21	89
Sustainable Fiberglass	FG	21	89
Kraft Faced Fiberglass	FG-KF	21	89
Rockwool	RW	32	89
Cellulose	SC	25	89
Low Density Polyurethane Foam	SPF-OC	8	89
Medium Density Polyurethane Foam	SPF-CC	30	89
Extruded Polystyrene	XPS-CC	21	76

within the attic and wall cavities. This fire incident is an example of sustainable design resulting in increased fire severity and damage. The insulation material was recycled denim (cotton) fiber. Other sustainable features also contributed to the extensive fire damage. For example, the roof had photovoltaic panels and lightweight engineered wood framing, which prevented critical firefighter access and caused a more rapid collapse, respectively [10].

1.4. Compartment fires

Insulation can prevent heat from escaping during a compartment (room) fire, which intensifies the fire and reduces the time to flash-over. But, if the insulation can maintain its thermal performance at elevated temperatures (without melting or burning away), it can also protect structural elements from the heat of the fire. In other words, a thermal insulator can both hurt and help during a compartment fire. Full-scale burn tests, as well as wall assembly experiments have been performed to assess the impact of various insulation types in a fire event [11–14]. Due to the nuance involved with insulation's impact in these scenarios, and the current debate on the subject, this paper will not incorporate such data into the assessment of the selected materials. However, future work will consider it.

2. Materials considered

The following is a list of the specific products considered in this paper. Composition of the materials considered are percentages by weight, and are those disclosed on the material safety data sheets (MSDS) for the product. The flame retardant chemical, if present, has been indicated by (FR). Table 1 provides the nominal density (ρ) and thickness (δ) for each material, based on manufacturer specifications.

2.1. Fiberglass

The fiberglass insulation is a flexible, fibrous batting sheet. Several fiberglass products were sampled. The first is a conventional, unfaced, fiberglass (FG-C), containing fibrous glass (78–97%), phenol, polymer with formaldehyde and urea (3–9%) [15,16]. Next, a sustainable, unfaced, fiberglass (FG), containing fiber glass (85–100%), and cured binder (0–15%) [17,18]. Finally, a sustainable, kraft (paper) faced, fiberglass (FG-KF), containing fiber glass (85–100%), cured binder (0–15%), and oxidized asphalt (facing adhesive) (1–5%) [17,19].

2.2. Rockwool

The rockwool insulation (RW) is a flexible, fibrous batting sheet, containing mineral fiber (94–99%) and cured urea extended phenolic formaldehyde binder (1–6%) [20,21].

2.3. Cellulose

Although cellulose can legitimately refer to any plant-based insulation, the industry term has evolved to refer to newspaper insulation. Modern-day cellulose insulation is made from recycled newspaper. The product sampled is a spray-applied, soft fiber pulp (SC). Product composition is recycled shredded-paper (82%) with sodium polyborate (FR) (18%) [22,23].

2.4. Polyurethane

The spray polyurethane foam insulation (SPF) is a rigid (once cured), expanding spray-on, foam. Two types were sampled. The low density SPF is an open-cell (SPF-OC) foam with components of tris-(2-chloroisopropyl)-phosphate (25–35%), surfactant (10–20%), tertiary amine (5–10%), and tertiary amine (1–5%). Flame retardant is present, but unspecified [24,25]. The medium density SPF is a closed-cell (SPF-CC) foam with components of hydrofluorocarbon (5–10%), tris-(2-chloroisopropyl)-phosphate (3–7%), triethanolamine (3–7%), trans-1,2-dichloroethylene (1–5%), tertiary amine (1–5%), 2-butoxyethanol (1–5%), Polyester Polyol ($\geq$1%), Non-halogenated flame retardant (FR) ($\geq$1%), Polyether Polyol ($\geq$1%), and tertiary amine (0.1-1%) [26,27].

2.5. Polystyrene

The extruded polystyrene insulation is a rigid, closed-cell (XPS-CC) foam panel. The XPS panel is composed of polystyrene (80–90%), HCFC-142b (7–12%), hexabromocyclododecane (FR) (0.5–1.5%), and Talc (0–2%) [28,29].

3. Insulation objectives

Several objectives for insulation must be evaluated to determine the most appropriate material for the specific application. Each objective comprises at least one attribute, and the nominal values for each insulation can be seen in Table 2. The values presented in Table 2 are for the stated density of the sample material. A value tree for the selection process can be seen in Fig. 2.

3.1. Thermal resistance

Thermal insulation's paramount attribute is its response to a temperature gradient. Standard practice requires insulating materials to be rated based on the thermal conductivity (k) and thickness (δ) of the product. The thermal resistance (R_{SI}) is determined through Eq. (1) and the standard test method, ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*, which measures the thermal conductivity of a material for a specified thickness and temperature difference [49]. The thermal resistance is listed in product specifications as the *R-value* and has units of h-ft^2 $-$ $^\circ$F-Btu^{-1} in the USA. Insulating products are tested at a mean temperature (average between hot and cold sides), T_m, of 75 $^\circ$F (24 $^\circ$C) for the published R-values. For convenience, all stated R-values have been converted to SI units, and will be referred to as R_{SI} (units of m^2-K-W^{-1}), for clarity.

$$R_{SI} = \frac{\delta}{k} \tag{1}$$

Due to changes in environmental conditions during operation, the thermal conductivity of the material will be affected. Studies show that the thermal conductivity of insulation varies linearly with changes in T_m. Thermal conductivity increases as the mean temperature increases. As a material's density increases, it becomes less susceptible to thermal conductivity changes with changes

Table 2
Insulation material objectives considered for comparative analysis among eight different products. Nominal values for each attribute are shown.

Objectives	*Attributes*	*Units*	*Materials*							
			FG-C	FG	FG-KF	RW	SC	SPF-OC	SPF-CC	XPS-CC
Thermal Resistance	k	10^{-3} W/m-K	39	39	39	34	40	39	21	29
	$\frac{\Delta k}{\Delta T_m \cdot k}$ †[c]	10^{-3} 1/K	6	6	6	3[a]	4	4	4[b]	5
	H_2O SORP ‡[c]	10^{-3} kg/kg	7.5	7.5	7.5	7.5[d]	240	16	20	4
	$\frac{\Delta k}{\Delta H_2O}$ *	10^{-3} 1/%wt	3[r]	3[r]	3[r]	1[r]	5[s]	3[d]	3[t]	1[t]
	Air PERM[c]	10^{-7} kg/m-s-pa	2500	2500	2500[d]	2500[d]	2900	0.042	0.0001	0
Fire Performance	FSI	N/A	25	25	70[d]	0	15	70[e]	70[e]	110[f]
	SDI	N/A	50	50	500[d]	0	10	500[e]	500[e]	500[f]
	$\dot{Q}''_{peak}$ #	kW/m^2	20[o]	20[o]	200[p]	10[o]	80[p]	200[q]	200[q]	300[o]
Cost	Installed Cost ⋆[g]	USD	\$2.83	\$2.83	\$2.83	\$3.86	\$5.02	\$8.28	\$9.71	\$14.06
Sustainability	Energy Use ⋆	MJ	19.5[h]	9.9[i]	16.7[j]	25.2[u]	26.2[l]	52.1[m]	97.5[m]	80.7[n]
	Water Use ⋆	kg	9.7[h]	4.8[i]	15.2[j]	6.3[u]	0.8[l]	457.0[m]	761.0[m]	37.9[n]
	Climate Change ⋆	kg CO_{2e}	0.76[h]	0.62[i]	0.75[j]	1.81[u]	7.83[l]	2.40[m]	25.65[m]	60.80[n]
Acoustic Damping	NRC	N/A	1.00	1.00	0.90	1.00[d]	0.80	0.70	0.20	0.20[d]
Durability	H_2O PERM‡[c]	10^{-10} kg/m-s-pa	1.72	1.72	1.72[d]	1.72[d]	1.78	0.875	0.0322	0.0122

All values from manufacturer's product specifications, unless otherwise noted. N/A = Not Applicable.
† Mean Temperature Effect on Thermal Conductivity ($\frac{\Delta k}{\Delta T_m}$)/($k$@24 °C).
* Moisture Effect on Thermal Conductivity ($\frac{\Delta k}{\Delta H_2O}$)/($k$@0%$wt$).
‡ Water Vapor Sorption and Permeability @ 23 °C. H_2O SORP @ 88% RH; H_2O PERM @ 90% RH.
# Representative, Rounded, Peak Heat Release Rate @ 75 kW/m^2 Irradiance in Cone Calorimeter.
⋆ For 1 m^2 @ R_{SI} = 1 m^{2}K/W.
[a] [30]; [b] [31]; [c] [32], unless otherwise noted; [d] No data available. See related section for explanation of value assigned;
[e] [33]; [f] [34]. Values are those calculated with inclusion of ignition of molten residue on furnace floor;
[g] [35]; [h] [36]; [i] [37]; [j] [38]; [l] [39]. Climate Change value extrapolated;
[m] [40]; [n] [41]; [o] [42]; [p] [43]; [q] [44]; [r] [45]; [s] [46]; [t] [47]; [u] [48].

in temperature gradients [30]. This phenomenon is a result of decreased air volume within denser materials, which reduces the contribution of convective and radiative heat transfer to the apparent thermal conductivity. The values, listed as $\frac{\Delta k}{\Delta T_m \cdot k}$, represent the mean temperature effect on thermal conductivity, relative to k at 24 °C.

As with fire, air infiltration into the cavity is a significant factor for thermal performance. However, if the cavity has been properly and completely sealed, the thermal performance of the insulation is not affected by the material type [31]. Again, proper installation and complete sealing of the space is required. Otherwise, the effective R-value of the insulation will be reduced by heat convection with air flow through the cavity. ASHRAE report RP-1018 lists air permeability for all of the materials sampled, except RW and FG-KF [32]. A separate study found no difference in air permeability between FG and FG-KF, therefore the value from ASHRAE RP-1018 for FG has also been used for FG-KF [31]. No additional published data could be found for air permeability of RW, therefore it was assumed to be the same as FG, due to similarity in material type (both mineral wools). Air permeability is denoted as Air PERM in Table 2.

Finally, moisture content can change thermal properties. Increased moisture decreases thermal resistance. Although this relationship is not necessarily linear for all insulating material types and densities, prior work indicates that it may be approximated as such for the products and material densities sampled, under likely

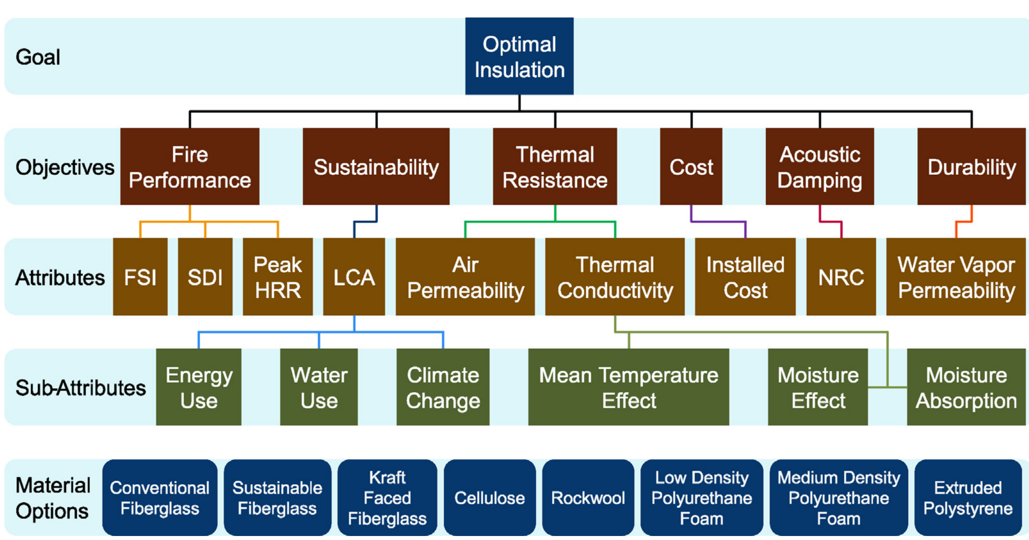

Fig. 2. The value tree for selecting an insulating material allows comparison of multiple material options through various objectives, each of which is comprised of quantifiable attributes and sub-attributes. Sub-attributes are additional quantities related to a specific attribute. For example, the LCA of a material has been quantified herein by three values: Energy Use, Water Use, and Climate Change.
FSI – Flame Spread Index; SDI – Smoke Developed Index; Peak HRR – Peak Heat Release Rate; LCA – Life Cycle Assessment; NRC – Noise Reduction Coefficient.

operating conditions [45]. Again, proper sealing of the cavity with moisture barriers can mitigate the inherent susceptibility of the insulation to moisture effects. Density will affect moisture's impact on thermal conductivity. The values given in Table 2, denoted as $\frac{\Delta k}{\Delta H_2O}$, are at or near the nominal material densities of the samples and are relative to k at 24 °C. No published data could be found for SPF-OC, therefore it was assumed to behave the same as SPF-CC. It should be noted that SPF-OC and SPF-CC have very different densities, which has been demonstrated to affect the sensitivity of thermal conductivity change with moisture changes for other materials [45]. Additional data is needed to confirm that SPF-OC does indeed exhibit similar behavior as SPF-CC, in this regard.

All insulation materials have been evaluated based on an ASTM test method, specific to their material type, for their moisture absorption. The type of test falls into two categories. The first is performed at very high relative humidities (RH) of 90% or 95% for 24 or 96 h and an elevated temperature of 49 °C (SC, RW and FG) [50,51]. The second is an immersion in water at 23 °C for 24 or 96 h (XPS and SPF) [52,53]. The disparate test methods result in incomparable values. Therefore, results from ASHRAE RP-1018 have been used instead. These values give an indication of the material's moisture uptake (denoted in Table 2 as H_2O SORP) under steady state conditions of 88% RH and 23 °C [32]. No additional published data could be found for moisture sorption of RW, therefore it was assumed to be the same as FG, due to material type similarity. When coupled with the material's thermal response to moisture, one can gain insight into the material's likely thermal conductivity change during extreme humidity events.

3.2. Fire performance

Concealed insulation in a wall or floor assembly must meet a minimum standard for flame spread and smoke development through a Steiner Tunnel test, typically ASTM E84, *Standard Test Method for Surface Burning Characteristics of Building Materials* or UL-723 [54,55]. The results of this test are a Flame Spread Index (FSI) and Smoke Developed Index (SDI) for the material. These indices are on a relative scale; asbestos-cement board having a value of 0 and red oak wood having a value of 100. Although this is the only fire test universally performed on individual building materials, there are several critiques of the method. The test is performed in a horizontal tunnel. If the specimen easily melts, such as thermoplastics (e.g. polystyrene), or is very thin, the results of the test may be mis-representative of actual fire scenarios [56].

The whole wall/floor assembly may be required to undergo the ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*, the consensus being that the exterior flame retarding wall (typically gypsum board in the USA) will provide a sufficient barrier between the heat of the flames and the concealed space contents [57]. In fact, some insulation is not required to meet the standard maximum threshold FSI of 25 or SDI of 450 if it is installed abutting the thermal barrier (e.g. kraft faced fiberglass). This test gives no indication of the insulation's impact in concealed space fires.

A more robust assessment of a material's combustibility and contribution in fire is the heat release rate per unit area ($\dot{Q}''$), given in Eq. (2). Using the standard test method ASTM E1354, *Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter*, one is able to measure a peak heat release rate ($\dot{Q}''_{peak}$), as well as many other properties in fire. In the simplest sense, the heat release rate per unit area can be considered as the product of the mass flux of volatilized fuel ($\dot{m}''_F$) and the heat of combustion of the fuel (Δh_c) [58].

$$\dot{Q}'' = \dot{m}''_F \Delta h_c \tag{2}$$

Some representative values of $\dot{Q}''_{peak}$ have been added to assess the materials studied in this paper. These values assume a fuel-lean environment, where oxygen supply is not limited because the cone calorimeter test is in such an environment. However, if a fire were to occur in a concealed space, the likely scenario would be a fuel-rich environment, in which $\dot{Q}''$ is limited by the air supply to the cavity. Therefore, the $\dot{Q}''_{peak}$ values provided are conservative. Further, these values include the presence of flame retardants (if applicable) in the materials. Unlike FSI and SDI, heat release rate can be used to model impacts of fuel sources in fire events [56]. However, there has been no requirement for product manufacturers to test for or publish such data. The FG-KF did not undergo the ASTM E84 test, hence the values listed in Table 2 for FG-KF FSI and SDI are assumed to be the same as SPF. This assumption is based on the similarity between $\dot{Q}''_{peak}$ for FG-KF and SPF, which suggests that they would exhibit similar FSI and SDI. Assuming these values for FG-KF is a conservative estimate.

3.3. Sustainability

Although an extensive list of accounting can be performed, three factors of environmental impact are considered here. These factors are considered from cradle-to-grave, with 100% landfill disposal as the last stage of product life. Total energy and water consumption, as well as CO_{2e} emissions are quantified for each material. Where available, these data are drawn from the specific product; otherwise, they are from a generalized study of a similar product (e.g. rockwool in the European market). The Functional Unit (FU) is based on 1 m^2 of insulation with an R_{SI} = 1 m^2-K/W. No integration of risk in the LCA has been done here.

It has been found that IAQ can be adversely affected by emissions from concealed materials [59]. Although material composition has been listed, further consideration of impacts to IAQ are not included in this assessment.

3.4. Cost

Although there are many attributes that can be considered in material selection, cost is a key factor. The relative cost of thermal insulation can be represented as the price per unit area and R-value. The costs listed in Table 2 are installed costs, based upon estimates for the Northeastern United States. Additional costs associated with air barrier installation are not included. Further, although the thickness required for the same R-value may influence the costs of other materials, such as the framing materials, it is not considered here.

3.5. Acoustic damping

Insulation may also serve as a barrier to sound transmission. ASTM C423, *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*, measures the sound absorption coefficient (α) at multiple frequencies for a certain material thickness and mounting condition [60]. Typically, the absorption coefficients at the 1/3 octave band center frequencies of 125, 250, 500, 1000, 2000, and 4000 Hz are measured. The Noise Reduction Coefficient (NRC) is the arithmetic mean, rounded to the nearest 0.05, of the sound absorption coefficients at four of these frequencies (250, 500, 1000 and 2000 Hz). This single metric gives an indication of the sound absorption capabilities of the material in a typical room environment (eg. human speech). Although a value of 1.00 indicates 100% sound absorption, often the NRC can be higher due to the specimen thickness [61]. All NRC values listed in Table 2 were calculated from mounting type A (ASTM E 795) test configurations [62]. NRC is the prior method, recently superseded by the Sound Absorption Average (SAA) in the current ASTM C423

Table 3
Normalized insulation material attributes based on the nominal values in Table 2. Two control scenarios and four weighting scenarios are shown. The first control scenario excludes both fire and sustainability objectives, and evenly weighs all other objectives. The second control scenario excludes only the fire objective, and evenly weighs all other objectives. Each of the four weighting scenarios increases the relative weight of a certain objective to emphasize either cost, thermal resistance, sustainability, or fire performance.

Attributes	*Materials*								*Control Scenarios*		*Weighting Scenarios*			
	FG-C	FG	FG-KF	RW	SC	SPF-OC	SPF-CC	XPS-CC	No Fire/Sustainability	No Fire	Cost	Thermal	Sustainability	Fire
k	0.0	0.0	0.0	0.3	0.0	0.0	1.0	0.6	0.125	0.091	0.077	0.200	0.091	0.091
$\frac{\Delta k}{\Delta T_m \cdot k}$	0.0	0.0	0.0	1.0	0.5	0.5	0.6	0.3	0.063	0.045	0.038	0.100	0.045	0.045
H_2O SORP	1.0	1.0	1.0	1.0	0.0	0.9	0.9	1.0	0.031	0.023	0.019	0.050	0.023	0.023
$\frac{\Delta k}{\Delta H_2O}$	0.4	0.4	0.4	1.0	0.0	0.5	0.5	0.9	0.031	0.023	0.019	0.050	0.023	0.023
Air PERM	0.1	0.1	0.1	0.1	0.0	1.0	1.0	1.0	0.063	0.045	0.038	0.100	0.045	0.045
FSI	0.8	0.8	0.4	1.0	0.9	0.4	0.4	0.0	0.000	0.000	0.038	0.056	0.045	0.167
SDI	0.9	0.9	0.0	1.0	1.0	0.0	0.0	0.0	0.000	0.000	0.038	0.056	0.045	0.167
$\dot{Q}''_{peak}$	1.0	1.0	0.3	1.0	0.8	0.3	0.3	0.0	0.000	0.000	0.038	0.056	0.045	0.167
Installed Cost	1.0	1.0	1.0	0.9	0.8	0.5	0.4	0.0	0.063	0.045	0.500	0.056	0.045	0.045
Energy Use	0.9	1.0	0.9	0.8	0.8	0.5	0.0	0.2	0.000	0.045	0.038	0.056	0.167	0.045
Water Use	1.0	1.0	1.0	1.0	1.0	0.4	0.0	1.0	0.000	0.045	0.038	0.056	0.167	0.045
Climate Change	1.0	1.0	1.0	1.0	0.9	1.0	0.6	0.0	0.000	0.045	0.038	0.056	0.167	0.045
NRC	1.0	1.0	0.9	1.0	0.8	0.6	0.0	0.0	0.063	0.045	0.038	0.056	0.045	0.045
H_2O PERM	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	0.063	0.045	0.038	0.056	0.045	0.045

standard. The SAA is more inclusive than the NRC, as it averages twelve sound absorption coefficients at the 1/3 octave frequencies from 200 to 2500 Hz. The SAA is also more precise, as it is rounded to the nearest 0.01 [61]. However, material data has not been updated to the new SAA method, therefore this paper reports NRC values. Values listed are for the nominal material thickness of the samples. The specific RW product selected did not have any acoustic data available, therefore the value listed in Table 2 is an estimate based on NRC data for other RW products from the same manufacturer (with similar density, composition, and thickness). The XPS-CC product also did not list acoustic data. Polystyrene is not generally regarded as a good acoustic insulator, therefore it is not tested or advertised as such. The NRC value for XPS-CC was taken from a similar (in density, composition, and thickness) closed-cell expanded polystyrene, made by a different manufacturer [63].

3.6. Durability

Commercially available insulation has been tested under various ASTM standards to meet minimum requirements of durability. Acceptable levels of corrosiveness, moisture absorption, microbial growth, vermin hospitality, etc. must be met. The reporting method for these tests is pass/fail, therefore it is hard to assess the variance in quality among materials. The National Association of Home Builders (NAHB) reports expected durability of all types of insulating materials will last or exceed the lifetime of the building [64].

Water vapor permeability (H_2O PERM) of the insulation may affect the durability of adjacent materials and the humidity of the indoor environment, however. These data have been added to provide some insight. Rockwool and FG-KF were not reported in the study, therefore these materials were assumed to behave the same as FG. This assumption is most likely conservative, in that FG-KF is more likely to prevent water transport (due to the facing) and RW is denser that FG (again preventing transport). However, it is unlikely that the true value for either varies significantly from the FG data (e.g. relative to the values for the plastics). Future work may include more emphasis on durability differences (e.g. compression degradation, decomposition, etc.), but is not considered here in full.

4. Methodology

In order to account for uncertainty in the nominal values (Table 2), additional data values (X) were gathered from multiple sources for each attribute (i) and material (j). Slight deviations from the previously stated nominal thicknesses, densities, and chemical contents might occur in these additional data sources. Further, if additional published sources were absent, a ±10% variation in the nominal value was assumed for the attribute and material. These data sets were then fitted with a normal distribution using the MATLAB command *fit probability distribution object to data* (fitdist), which creates a probability distribution function (pdf) by fitting a specified distribution to a data set ($X_{i,j}$). Data sources included in the pdfs, but not directly cited in this paper are [65–72]. Next, a Monte Carlo simulation was run for 2000 samples, each time randomly sampling the normally distributed data for each attribute and material. This simulation was performed using the *inverse cumulative distribution function* (icdf) command in MATLAB, which returns the icdf of the pdf, evaluated at a probability value specified with the *uniformly distributed random numbers* (rand) command, which returns a single uniformly distributed random number between 0 and 1. For each sample, the data were normalized (X') relative to the range of values for all materials (Table 3). Eqs. (3) and (4) provide the normalization equations, on a scale from 0 to 1, with 1 being assigned to the best performing material(s) and 0 to the worst material(s) in that attribute category. Eq. (3) was used if a higher attribute value was preferable (e.g. NRC) and Eq. (4) if a lower value was preferable (e.g. FSI).

$$X'_{i,j} = \frac{X_{i,j} - X_{i,\min}}{X_{i,\max} - X_{i,\min}} \tag{3}$$

$$X'_{i,j} = \frac{X_{i,\max} - X_{i,j}}{X_{i,\max} - X_{i,\min}} \tag{4}$$

Each objective was then weighted based on the relative importance given, with the total weight (w) over all objectives summing to 1. Each material was subsequently ranked ($\bar{x}_j$) based on the sum of its weighted attributes.

$$\bar{x}_j = \sum_{i=1}^{n} w_i X'_{i,j} \tag{5}$$

These rankings were normalized ($\bar{x}'_j$) by sum to unity over all material rankings.

$$\bar{x}'_j = \frac{\bar{x}_j}{\sum_{j=1}^{m} \bar{x}_j} \tag{6}$$

Hence, an average performer would receive a ranking of 0.125, since there are a total of eight materials considered. Finally, after performing this series of calculations on each material for 2000 random data samples, the mean and twice the standard deviation

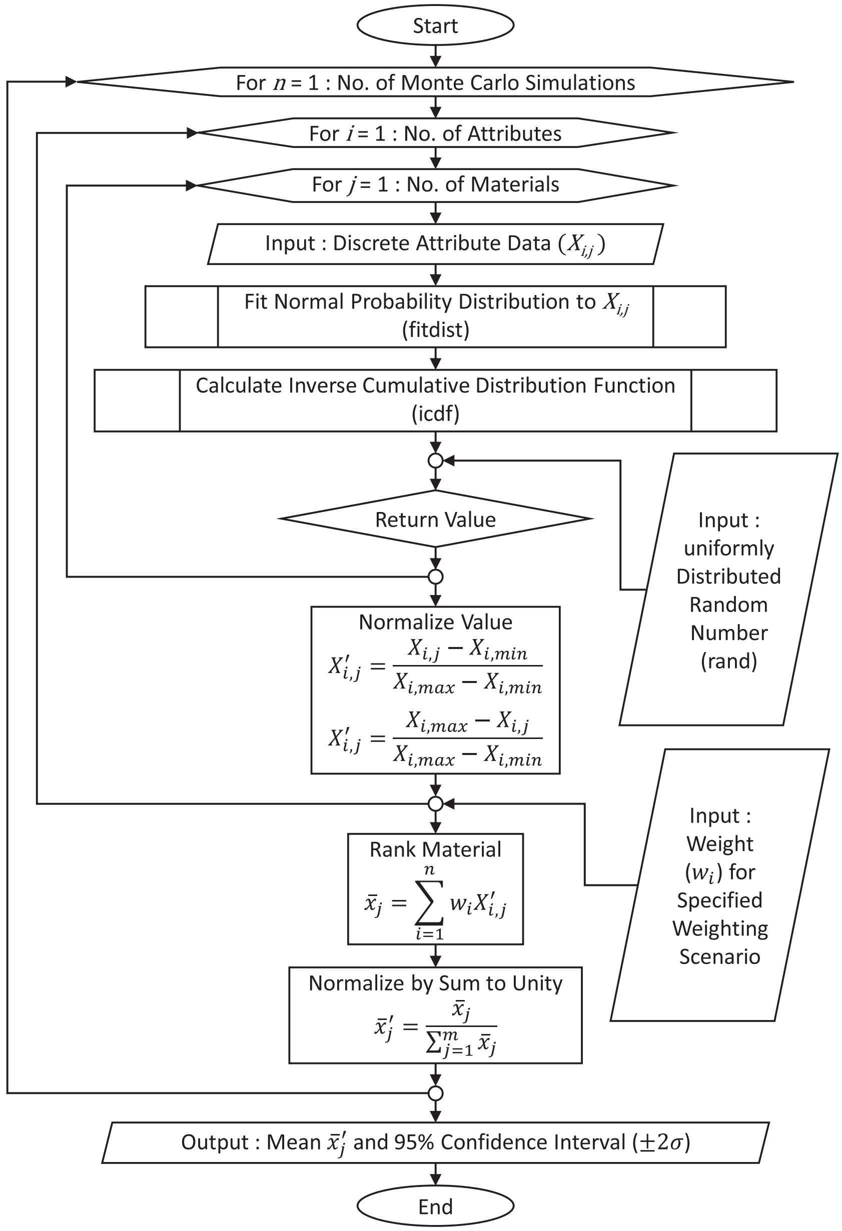

Fig. 3. Flowchart summarizing the methodology developed to rank and compare eight different thermal insulation materials based on performance in multiple objectives.

($\pm 2\sigma$) of the samples provide the final material ranking and 95% confidence interval, respectively. The uncertainty (95% confidence interval) results are preliminary, as data sets from literature are limited in this early development of the tool. Table 3 gives the chosen weights for each attribute. These weights may change based on the particular desires or needs for the specific project. As such, these weights may be altered and used in the weighted mean equation (Eq. (5)) and subsequently in the normalization equation (Eq. (6)) to find the overall ranking ($\bar{x}$) of each insulation sample.

First, two control weighting scenarios were performed. In the initial control case, neither the fire performance nor sustainability objectives were considered in the weighting scheme. All of the remaining objectives were given equal weight, and then the materials were ranked. This first control scenario is meant to demonstrate a traditional frame of insulation selection where the decision maker is unlikely to consider the sustainability or fire safety of the material. For the second control case, the sustainability objective was introduced, but fire performance was still not considered. For this case, all of the remaining objectives, along with sustainability, were weighted equally to calculate material rankings. This second control scenario represents the current sustainability community's selection of insulation, where an additional object of sustainability would be weighed with the traditional objectives.

To further the analysis by introducing the concept of fire safety as a component of sustainable design, all objectives (including fire performance) were weighted in four different objective weighting scenarios. The first is with a high emphasis on cost, the second with a high emphasis on thermal resistance, the third with a high emphasis on sustainability, and the fourth emphasis is on fire performance. In each of these scenarios, a total of $w = 0.5$ was assigned to the emphasized objective, with the remaining weight ($w = 0.5$) evenly distributed among the other objectives. These scenarios were chosen as a demonstration and the weighting scheme presented herein is somewhat subjective. Future work will benefit from incorporation of statistics to determine more appropriate relative weighting of insulation attributes.

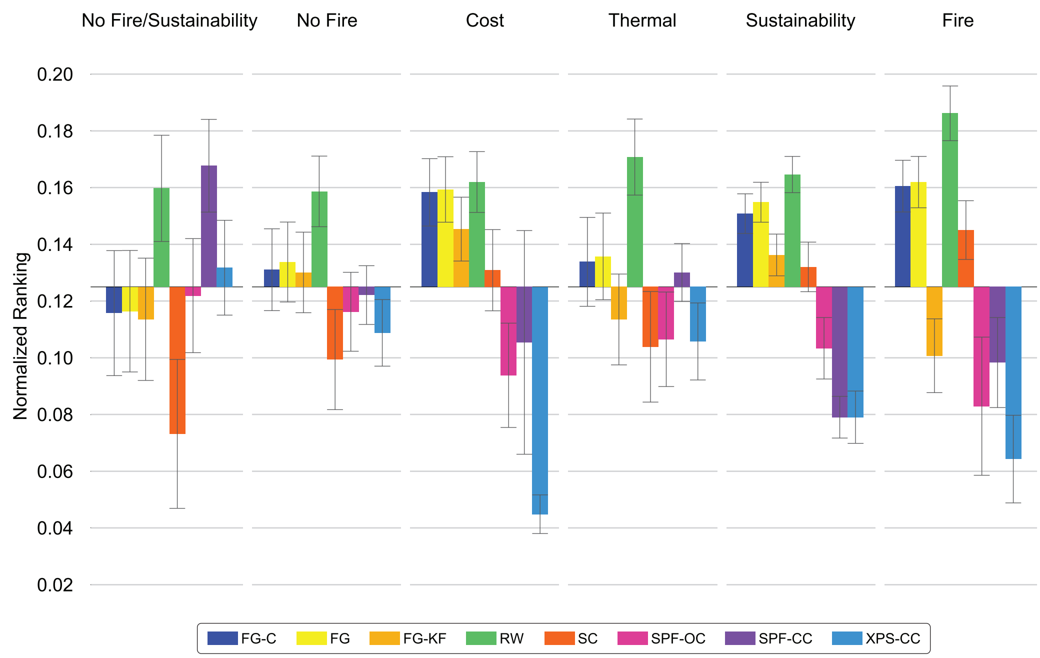

Fig. 4. Normalized insulation rankings with 95% confidence intervals. Two control cases and four weighting scenarios are shown. The first control scenario excludes both fire and sustainability objectives in the weighting. The second control scenario excludes only the fire objective. Each of the four weighting scenarios increases the relative weight of a certain objective to emphasize either cost, thermal resistance, sustainability, or fire performance. An average performer would receive a ranking of 0.125. Therefore, any material above the 0.125 baseline demonstrates good performance in that scenario.

In all of the previously described weighting scenarios, the attributes comprising an objective equally received a portion of the weight. For example, in the fire emphasized case, the 0.5 weight was evenly distributed between FSI, SDI, and $\dot{Q}''_{peak}$. An exception exists with the thermal resistance objective, where the attributes of H_2O SORP and $\frac{\Delta k}{\Delta H_2O}$ were always counted as one combined attribute due to their interdependence (each receiving half the weight) and k was always counted as two attributes due to its significant role in insulation quality (receiving double the weight of the other attributes within the objective).

A summary of the methodology is outlined in Fig. 3.

5. Results

The normalized rankings for each material under each weighting scenario can be seen in Fig. 4. Starting with the first control case, where neither fire performance nor sustainability objectives were considered in the weighting scheme, the best performer is SPF-CC (medium density polyurethane), while the worst performer is SC (cellulose). These results are in line with standard industry expectations. SPF-CC is highly regarded for its thermal resistance attributes, while SC is best known for its sustainability, however lacking in other performance categories [73–75]. What these results demonstrate is that, without consideration for both the fire safety and sustainability of the material, SPF-CC is only rivaled by RW (rockwool).

Next, introducing the sustainability objective in the weighting scheme, but still neglecting fire performance, the results change starkly. SPF-CC no longer maintains its top position, which may be unsurprising since the LCA for polyurethane is poor. The result for SC was less predictable, however, as cellulose is still not a top performer with sustainability included. It is important to note here, that sustainability is simply included, but not emphasized, in this second control scenario. Therefore, the conclusion is that, all objectives being equal, the sustainability of cellulose does not sufficiently counteract its poor performance in other areas.

In the four remaining weighting scenarios, RW was the best performer in every case. The fiberglass materials were above average performers in every case, although kraft faced fiberglass was below average when thermal resistance or fire performance were emphasized. Cellulose was also an above average performer in three of the four weighting scenarios. When thermal resistance was emphasized, cellulose was the worst performer. This was also the only scenario in which closed-cell polyurethane was above average. The XPS-CC (extruded polystyrene) did not perform well in any scenario. Although these results may seem counterintuitive to industry preferences, part of the disparity can be explained by the inclusion of both sustainability and fire safety in all four of the weighting scenarios herein demonstrated. These two factors, frequently overlooked, can be seen here to have a fairly significant impact on the insulation of choice. However, this impact is significant because of the import placed on these factors, which may not be justified in all building projects.

6. Conclusion

Several thermal insulating products were selected and assessed relative to one another based on their performance characteristics. Attributes, such as thermal conductivity and NRC, were normalized and subsequently weighted relative to each other in four different scenarios. Each scenario emphasized an objective, i.e. performance area: cost, thermal resistance, sustainability, and fire safety. A control case scenario demonstrated the performance of the materials when neither fire nor sustainability are considered, with the remaining objectives equally weighted. A second control scenario showed the rankings when sustainability is introduced as an objective. Based on the extensive, but not exhaustive, list of attributes considered, rockwool (RW) was the best performer across the board.

Generally speaking, fiberglass was an above average performer in all of the weighting scenarios. The kraft faced fiberglass (FG-KF), however, performed below average when either thermal resistance or fire performance were emphasized. Looking at the data, it is clear that the low performance when thermal resistance was emphasized indicates that its poor fire performance is still weighted heavily enough to counteract the positive traits in its thermal resistance attributes. Without considering both fire performance and sustainability in the weighting, none of the fiberglass batts performed above average.

Rockwool was the clear winner in all weighting scenarios, except the control case in which fire performance and sustainability were ignored. In that case, RW was still the second best performer.

Cellulose was a mix of above and below average performance, depending on the weighting scenario. In other words, the ranking of cellulose is highly dependent on the objective emphasized. In both control cases (no fire/sustainability and no fire) cellulose was the worst performing material. However, when either fire, sustainability, or cost were emphasized, cellulose was an above average performer. The surprising case was when thermal resistance was emphasized. In this weighting scenario, cellulose was again the worst performer. Although cellulose has a number of high performing objectives, they do not overshadow the poor overall thermal performance of the material.

The low density polyurethane (SPF-OC) was consistently a poor performer in all weighting scenarios, because it has thermal resistance on par with the mineral based insulations (due to its open-cell formation), while having relatively poor cost, fire, and sustainability attributes, like its closed-cell counterpart (SPF-CC). The closed-cell polyurethane, not lacking in thermal resistance, was the best performer in the control case without fire or sustainability considered. It also scored above average when thermal resistance was emphasized. However, SPF-CC was tied for worst performer when sustainability was emphasized.

Overall, extruded polystyrene was the weakest performing material. When cost, sustainability, or fire were emphasized, extruded polystyrene (XPS-CC) was the worst performer. However, without consideration for both fire and sustainability objectives, polystyrene was an above average performer.

Future work will add several more attributes to enhance the tool. Indoor air quality effects of the insulating materials will be considered, as well as the recycled material content and sourcing. These additions might reduce the performance of rockwool and conventional fiberglass, as there is some concern over the use of formaldehyde in the binding agent, among other potentially harmful chemicals. More emphasis will be placed on durability by increasing the number of attributes in the objective category (e.g. compression degradation, decomposition, etc.). Durability attributes will likely improve the ranking of XPS-CC, as it is a more rugged material known to perform better than others in harsh environments. Addition of other materials, such as recycled denim cotton insulation, will also improve the tool. Further, assessing the effect of insulation on a compartment fire, and quantifying the results, will improve the fire performance objective. Lastly, space constraints can be a factor in material selection. Retrofits or irregular spaces may require a spray applied insulation. Also, achieving a particular R-value will require different wall thicknesses and framing size for different materials, which may be a consideration in selection if a certain R-value is required. These issues need to be quantified and introduced into the tool.

In addition to increasing the number of attributes, improvements to the uncertainty analysis will be made by increasing the data sets for each attribute. Finally, a sensitivity analysis of the weighting scenarios will be performed and through that an improved weighting scheme can be achieved.

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