Technology Assessment of Insulation Material for Home Construction

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Abstract

Depleting energy sources is alarming many governments, organizations, and companies to set ambitious goals to reduce their energy use over the next few years. Buildings consume significant portion of energy. One of the most practical strategies to reduce buildings' demand for energy is by avoiding heat losses and implementing energy saving measures. Today's high performance insulation and thermal design can dramatically reduce heat losses. Many technical solutions are already available and applied across all regions, both in new build and renovation. The choice of the most appropriate insulation product has to be decided on a case-by-case basis as it largely depends on the building type and design and climate zone. This paper conducts technology assessment for different type of insulation technology that fits different construction application. Traditional and modern insulation technology has been discussed across this

research. R&D recommendations are presented in the conclusion section of this report for improving manufacturing process of new high performance insulation materials to be able to compete in the insulation market.

Introduction

Use of the excessive source of energy in our planet helped with the expansion of human population and technology advancement. Societies through history have built a broad infrastructure, which needs energy supplies for its proper functioning. Along with this was the developed and inherited practice of aggressive energy consumption in daily activities of industry, commercial, and private life. When energy sources begin to deplete at a rapid rate, it became important to realize how societies will manage for adjusting to the limited energy sources left. In that matter, some effort has been made to establish new habits towards more efficient energy practice on organizational and personal levels. Many research and technologies has been utilized to reduce energy consumption in commercial and residential sectors [1]. Space cooling and heating systems in residential building become a necessity over time, thus they account for most part of energy consumption. The following Figure 1 shows by which portion the HVAC is contributing in energy consumption in residential buildings. The percentage of HVAC usage depends on many factors e.g. the climate zone in which the building exist and the age of the building which determine the level of technologies that could be used in its construction. Insulation in wall, roof, pipes, and frames play an important role in limiting the amount of energy leakage.

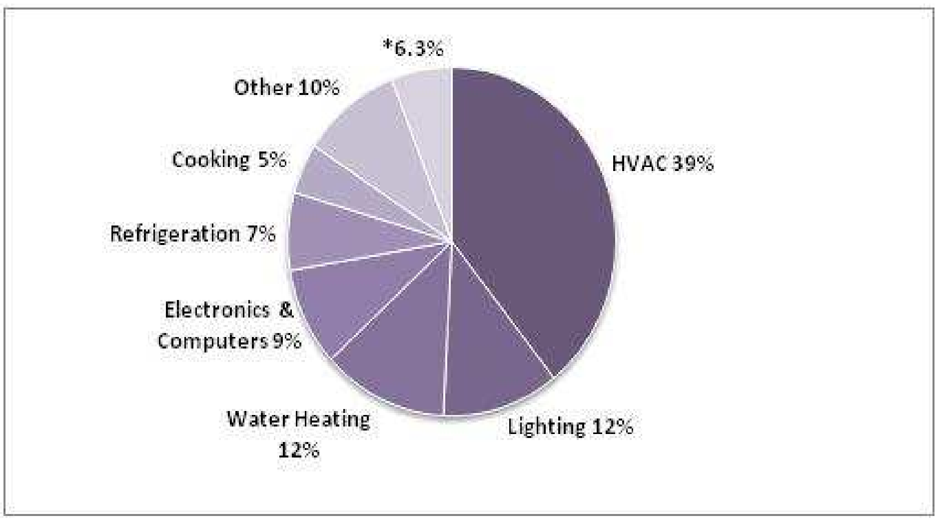

Figure 1: Energy consumption percentages in a common house hold [1]

Problem statement

Maintaining buildings' coolness in summer and warmness in winter, while reducing energy cost is a challenge. Almost half of the energy consumed is used on HVAC. Some of that thermal energy is wasted by simply leaking out or in the building. One of the methods to prevent that and therefore increasing the energy efficiency is applying insulation technology in construction. Insulation helps to reduce the energy consumption of heating and cooling systems while achieving better living comfort. Effective insulation protects the environment and reduces greenhouse gas emissions by lowering energy consumption [2]. The industry today is in need for better energy efficient insulation technologies to meet newer energy star standards and demands. Many type of materials are used to insulate houses and there are even more manufacturing techniques that give these materials various capacities. These capacities are large numbered and it is difficult to compare to achieve the best insulation solution for different application.

Research objective

According to the Department of Energy, heating and cooling systems use about half of the energy consumed in American homes [3]. Typically, 42% of the average family's utility bill goes to keeping homes at a comfortable temperature. The energy sources that power these heating and cooling systems emit more than 500 million tons of carbon dioxide and 12% of the nitrogen oxide emissions [3]. Improving energy efficiency in residential buildings by using insulation is the simplest and most cost effective way to reduce energy consumption. Using insulation does not require energy to save energy unlike other energy efficient products [3]. Providing suitable insulation is one of the most important home improvements considering the rise in prices for energy units. This paper will assess different insulation technologies and materials for new house construction to reach higher energy efficiency.

Project scope

The scope of this research to assess different insulation materials used in home construction. The assessment will include materials available and commonly used today. In addition, this research will study newer materials that are recently introduced in the market or still in R&D phase.

Limitation:

The authors based this research on literature review to assess the different insulation materials. There are many literature resources available today on the different types of insulation materials. To complete this assessment the authors selected a sample of insulation materials that best represent most available products. The assessment is narrowed on materials commonly used in new home construction buildings.

The study will focus on the most important criteria when assessing the different insulation materials. For this reason the selected criteria and materials are limited to outer house wall and ceiling applications. Other special use insulation materials were excluded from this research.

The cost data of insulation materials in this research include purchase prices and installation. This does not cover the cost of long term sustaining of the material if needed. Another limitation in this research regarding scoring of the materials cost is that the authors used a four-point scale which does not always represent the accurate quantitative comparison. Below is a summary of the research limitations:

- Research based mainly on literature review
- There many building insulation material that could not be included in this research
- Geographic locations and weather differences were not considered in this research
- The criteria's studied n this research is small sample of the more important criteria's

- Cost estimates based on initial installation of materials for this research

Structure of the report

The report considered three perspectives to categories thermal insulation criteria, technical, environmental, and organizational. A gap analysis is presented to identify areas for development and improvement in next generation of insulation materials. Next, the report presents a technology landscape of existing insulation materials. The authors scored each of the materials against a selected set of criteria, followed by a hierarchical decision model (HDM) to identify the most important criteria for selecting an insulation material. After that, a conclusion of the report is presented with recommendations for future R&D to improve insulation materials based on the studies final results. In addition, the authors suggested areas for future research and studies in assessment of insulation materials.

Study Methodology

The assessment of different insulation materials and technologies are realized with an emphasize of using a multiple perspective approach. A gap analysis model is used to identifying the needs in Insulation materials. This gap analysis gives an overview of the different construction insulation technologies and materials. These materials are then categorized in the technology landscape analysis.

To prepare the assessment model we reviewed multiple insulation technology evaluation criteria in literature. Using the multi perspective approach, we were able to organize the criteria in three perspectives. In this study the authors used combined approaches of HDM and scoring to assess different technologies and material of thermal insulation in the construction sector. The researcher were faced with a mix of qualitative, quantitative, and sometimes conflicting factors in scoring the different materials that are taken into consideration in thermal insulation technology. In that facet the team needed to capture insulation expert's opinion to evaluate the importance of the defined criteria of insulation materials and technologies.

Multiple Perspective Approach

Multiple perspective approach is introduced to support the decision making and enables researcher and decision maker to view the problem environment. The multiple perspectives will enhance the ability to make better-informed choices. This model provides a feasible framework that decision-makers and researchers can use to better understand and facilitate multiple perspectives in decision-making. The team attempt to structure the Hierarchical Decision Model in light of the multiple perspective approach. Using this approach, we define a broad terms to cover multiple viewpoints. For this particular research the team used three perspectives to categories thermal insulation criteria: Technical, Environmental, and Organizational.

- Technical Perspective: Criteria that relate to technical performance
- Environmental Perspective: Criteria that have an impact on the environment
- Organizational Perspective: Criteria that make up political motivation, policies and regulations, market special interests, compliance, and security

Gap analysis

As mentioned earlier that the technology gap analysis will be used to identify the needs for future technology and the differences in current technology situation. The gap analysis should be conducted to achieve the technology objective. By identifying the gap, it will provide the possible direction of the technology to improve in the future. In order to create Gap analysis, there are three steps that need to be considered. The first step is specifying the needs of the technology. From this step, the future state or place where the technology should be at will be stated. Second, the current situation for each need will be analyzed to see how the technology can perform in nowadays. Finally, the gaps will be identified by comparing the need for future state and the current state of the technology [4].

Technology landscape analysis

A landscape analysis model presents current state for the area of interest and is used to research the area of study. Dimensions and key criteria and features are identified. This landscape will also identify potential alternative options and how they are related. It will also present possible strengths and/or weaknesses for each alternative.

Scoring model

The scoring model is a method to evaluate and rate several alternatives by having several command variables. The distinctive feature of a scoring model is the ability to put values for assessment criteria that are not measurable or expressible in numbers [5]. It is possible to directly compare qualitative and quantitative attributes and features after translating them all in the same scoring scheme. At the beginning of a scoring process, a scoring scheme and a scoring range has to be defined. The scoring scheme can either consist of numbers, for example from 1 to 10, or it can also consist of words, for example starting from bad over poor good to perfect. The challenge in scoring is to categorize the subjective and quantitative features of a product or a technology into the chosen scoring scheme.

Scoring is a heuristic method to compare and rate different independent products, technologies, opportunities, etc. The advantages of scoring are the traceable and comprehensible procedure and the simple and easy way to conduct further comparisons with the scored items. The main disadvantages in this method are the difficulties to score some subjective criteria and the intimateness of a score when it is done. Other problems are the conflict potential in scorings done by more than one expert and the fact that not all criteria are mostly of the same importance. So adding all scores to a final score for one study objective can lead to biased and unbalanced results [5].

Hierarchical Decision Model

Hierarchical Decision Model (HDM) is a strategy decision tool to provide direction in strategic planning. The HDM was developed by the Engineering and Technology Management department at Portland State University. The software associated with the HDM creates a special record to collect evaluations from each participant, and displays participants' pairwise comparison for each level of the model. This model simplifies complex decisions, captures judgments of decision makers and identifies opinion's similarities and differences. In a typical HDM procedure, there are six stages of research. The stages that the decision making process should go through using HDM are modeling, expert panel selection, data collection, analysis of results, sensitivity analysis, and validation. The benefit of crafting the decision model with the input from the experts is that it enables to express the strategy concept and comparing the long-term and short-term objectives. In addition, it also enables to identify agreements and disagreements among experts. Crafting HDM demonstrate opinion's similarities and differences, and it help to present them to be discussed or resolved. The structure of HDM consists of mission as the final goal of the decision model, objectives to fulfill the mission, the criteria for each objectives and alternatives as initial target for decision making. This structure helps decision makers choose the best solution among several alternatives across multiple criteria.

Model implementation for insulation material assessment

The assessment of insulation technologies and materials for house construction is described in the following chapter. The methodology for the assessment is based on the methods presented in the previous chapter. The core of the model is the parallel conducted scoring and HDM by using the same categories and criteria in both analyses. Thereby we are able to determine the performance of the insulation types on the one hand and on the other hand we will get results for the weight and the importance of each criterion.

Gap analysis

After the project objective is selected, the direction of the project needs to identify. The best way to know which direction the insulation technology should be in the future is conducting the gap analysis. In this research, the needs for future insulation technology and the capabilities of current technology will be based on the multiple perspectives; technical, environmental, and organization. In each perspective, the needs will be the same as the criteria in scoring method and HDM that will be describe later. However, in each needs, it will contain sub-criteria in order to better understand it. Then, other research papers will help to analyze the current technology capabilities. After that, the gap between the needs and the capabilities will occur. Therefore, the direction of the insulation technology will be identified in order to meet the project objective.

Technical Perspectives

In technical perspective, thermal performance will focus on the thickness and thermal conductivity value of the material. For the better performance of the material, the market needs for insulation material to be thinner and lower conductivity. Cost of insulation material and installation will be considered because some of material is cheaper than another, but there are problems with its life-cycle cost because the cheaper material is easily to damage and need to be replaced during its life-cycle. Moreover, because different climates need to install different insulation materials, and some materials cannot be used in some areas due to the moisture issue, the new insulation material should be improved to be more adaptable in various climates. The final criterion is ease of construction. In this criterion, the new insulation material should be fast and easy to install and maintain during its life cycle. Moreover, it should decrease the air leakage and thermal bridging after install at construction site. Table 1 is illustrated the gap of technical perspective for insulation technology.

Table 1: Gap analysis, Technical Prospective

Needs	**Capabilities**	**Gaps**
Thermal Performance **- Thinner insulation materials with same performance** **- Lower thermal conductivity without increasing the thickness**	- The thickness of insulation will depend on R-value and range of thermal conductivity [6] - For traditional material, polyurethane has lower thermal conductivity from 20 -30 mW/(mK) [7] - For state-of-art material, it has thermal conductivity less than 4 mW/(mK) such as VIP and aerogel [7]	- Evaluation of insulation material that has better R-value without increasing thickness - Improved in thermal conductivity material
Cost-effective insulation methods	Total costs per square foot: $1.18 - $1.58 for wall [8], $1.26-$1.7 for attic [9]	- Reduction in material and installation costs - Reduction in the life-cycle costs of insulation
Durability **- Applicable insulation material for all climate zones**	Different climate zones use different insulation materials [10]	Evaluation of liable material (properties change with temperature and humidity)
Ease of construction **- Fast and easy to install** **- No air leakage and thermal bridging** **- Easy to maintain during life cycle – easy to replace**	- Depends on insulation type: foam, batts, rigid panels, etc. - Mostly need of professionals [6] - Proper installation is important for performance of insulation [11] - Most insulations are included in the walls or roof that is hard to replace and maintain [6]	- Evaluation of new technology that easy to install and no need for professionals - Evaluation of installation methods or insulation materials that automatically avoid air leakage or thermal bridging - Improved the maintenance method

<u>Environmental Perspectives</u>

In environmental perspective, the research will focus on life-time and recycle impacts of the materials. The new insulation material should be environmental friendly and not contain or include hazardous chemicals. Hazardous chemicals can have negative affect on recycling the materials and then they cannot be recycled. An example is the added fire-retardant chemicals on cotton and/or cellulose insulation. Table 2 is dictated the gap between the needs and capabilities for environmental perspective.

Table 2: Gap analysis, Environmental Prospective

Needs	Capabilities	Gaps
Life-time impact	- Some of material use CFCs, HCFCs, and CO2 when installed that is hazardous gas [12] - Specific treatment need to use to dispose the material ex. Extruded polystyrene [12]	- Materials that are environment friendly when disposed and installed
Recycle impact	- Fiberglass is semi-hazardous and difficult to recycle [12] - Recycle materials are usually coated with fire- retardants that cannot be recycled [13]	- Easer recycling material and procedure

Organization Perspectives

The last perspective is organization. The criteria that this research paper focused are availability of the material and building code requirement from government. Nowadays the incentives from government are not enough for the residents to install or upgrade to new type of insulation material. Moreover, some materials are not widely available in the market because lacking of the support. Also, the health and safety issue and fire and humidity resistance should be included in the regulation for new insulation materials. The gap analysis for organization perspective is shown in Table 3.

Table 3: Gap analysis, Organization Perspective

Needs	Capabilities	Gaps
Availability **- Increased government incentive** **- Increased adoption rate of high efficiency material**	- Limited Government incentives such as Fed: tax credit of up to \$500 or 10% [14] - the state-of-art materials are not commonly used in the market	- Improved Government incentives - Large available market for higher efficiency material
Building Code Requirements	- Regulation on dust for respirable dust: 5mg/m3 and total nuisance dust: 10mg/m3	- Included the regulation of health and safety in the new

- Increase occupant health, comfort and safety **- Fire-resistance** **- Effect as vapor barrier**	and fiber: 1 F/ml [15] - Some of material produce toxic in case of fire such as extruded polystyrene and polyurethane foam [12] - Fire class between A1-B2 depend on material [15] - Resistance of vapor diffusion varies from the factor of 200 [15] - Cellulose is easily to damage when contact with moisture [16]	material - Included A1 class fire-resistance requirement - Included humidity resistance requirement

Technology landscape analysis

The type of insulation materials differ in many criteria including thermal performance, the ability to apply in the construction site, form and shape, fire and temperature resistance, cost, durability and many more. The authors use the technology landscape to categorize the several insulation types. The insulation materials included in this research are divided in two groups, the traditional and state-of-the-art materials [7]. Materials in the traditional include commonly used insulation for construction in today market. Materials in the state-of-the-art group are the newer insulation technologies that are still not used in construction but are with promising features for use in this field. As shown in Figure 2, the traditional materials are further divided to four technology groups by application type. Group 1 includes the foam materials; Polystyrene, Polyisocyanurate, PUR and Phenolic. As the name implies, the materials in this group are liquid that will convert to foam when applied on site and then convert to solid. Group 2 includes batts material; Fiberglass, Rockwool, Cotton and Polyethylene. The materials in this group are sold and delivered to site in large rolls. Group 3 includes rigid board; EPS, XPS, Polyisocyanurate, Fiberglass, PUR and Perlite. This type of material is delivered in large board form and then cut to size on the construction site. Finally, group 4 is the loose fill materials; Fiberglass, Rockwool, Cellulose and Perlite. These are in the form of lose material. There are four promising state-of-the-art material chosen for this research; Aerogel, Vacuum Insulation Panels (VIP), Gas Filled Panels (GFP) and Phase Change Materials (PCM) [7].

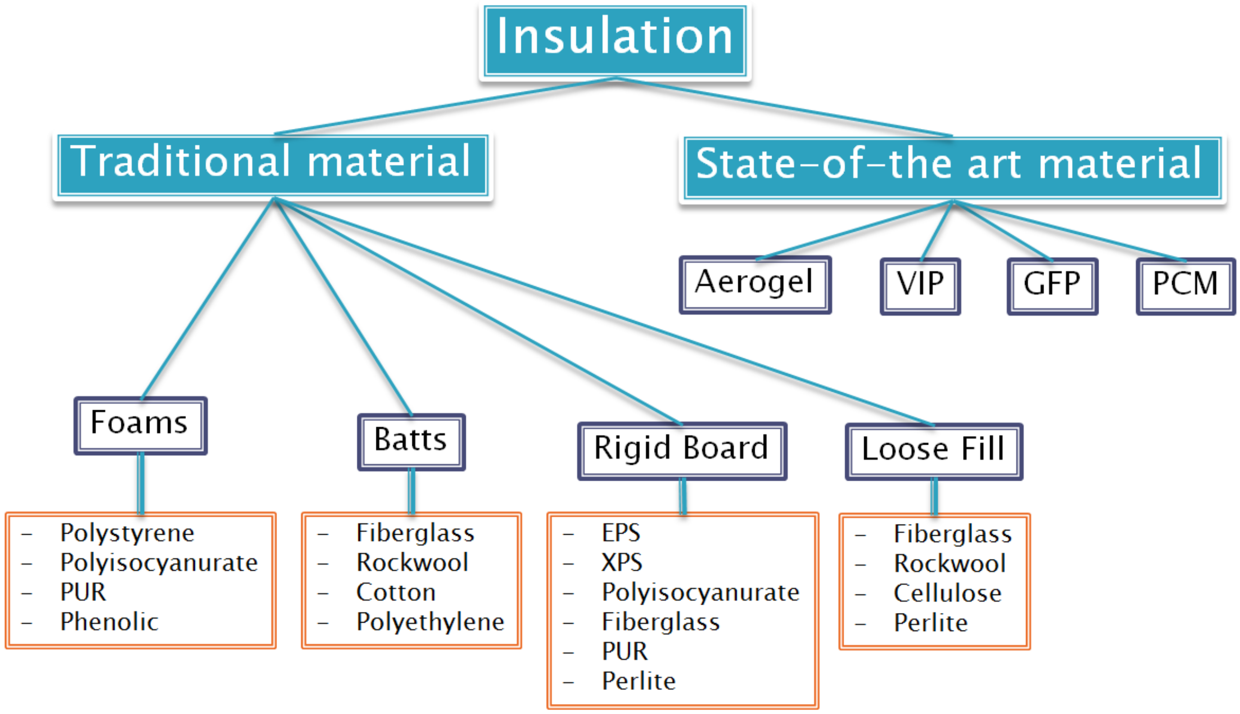

Figure 2: Insulation materials landscape

The following sections will further describe the different insulation technologies and materials like they are grouped in the technology landscape.

Traditional Materials

Foam insulation material

Spray foam is made by mixing two or more liquid chemicals. The mixing and reacting materials respond quickly and expanding to create foam that insulates air seals and provides a moisture barrier. Spray foam insulation is known to resist heat transfer well, and it offers a highly effective solution in reducing unwanted air infiltration through cracks, seams, and joints [17]. There are different types of spray foam, which are basically either high pressure foam and/or low pressure foam. Different types of foam could be installed in existing or new constructions. Different types of foam are suitable for different applications. The liquids are delivered in different drums or containers to the construction location to be mixed and reacted; the result will be expanded foam. This process required a professional worker [17].

Batts insulation material

Batts, roll or blanket insulation is one form of insulation material that is the most common used and available, and also relatively inexpensive [13]. It can be manufactured from various materials such as fiberglass and Rockwool. This type of insulation is delivered in very large roll with the width that suit with standard spacing of wall studs [6]. However, the insulation is easier to install when compared with other types. The home owners can install it themselves, by cutting or trimming the batts, or hire a professional installer [13]. The facing of the batts, such as foil-kraft paper, vinyl and flame-retardant facing will be used to act as a barrier from air, moisture and fire. It can be installed to unfinished wall, floor, and ceiling. The big concern when using this type of insulation is that its thermal performance tends to decrease easily. The R-value will decrease when pressing or cutting the batts and also thermal bridging will occur between cut edges [18]. Thus, this insulation type need to be installed carefully when there are joist spacing and other obstruction such as wires, electric boxes, and pipes in the wall. In this research paper, the materials that will be considered for scoring methodology are fiberglass, Rockwool, cotton and Polyethylene.

Rigid board insulation material

Rigid insulation panels and boards are made out of fibrous materials or foams [12]. The big difference to the already described foam or batts insulation is the rigid shape of the panels. They are all pre-manufactured and come in boards or panels to the construction site. So they are pretty simple to install by only putting or gluing them on the walls that should be insulated [19]. Many board insulations are faced with reflective foils to increase the thermal performance or with a water resistant layer to use it as a vapor barrier [6]. Rigid board insulation is often used in pre-fabricated structures, as insulative wall sheathing and it is widely used for foundation insulation. Materials to produce rigid board insulation are mostly overlapping with foam insulation materials. The most established materials that are reviewed in the following scoring model are Expanded Polystyrene (EPS), Extruded Polystyrene (XPS), Polyisocyanurate (ISO), fiberglass, Polyurethane (PUR) and Perlite.

Loose fill insulation material

Loose fill materials chosen for this study are fiberglass, Rockwool, cellulose and Perlite. These are available in the form of loose material and spray installed on site, Figure 3. Some of the loose fill types can be sprayed either dry or wet depending on the area it is going to installed at. Usually it is installed dry in roofs. The wet feature is useful when installing the material in vertical walls.

Figure 3: A construction worker spraying loose fill insulation material in the roof of a new construction [20]

Fiberglass is high in thermal insulations properties. Rockwool is made from natural materials and is allergy free safe on the environment. Cellulose products are made from old newspapers that are shredded and sold as loose fill insulation materials. It is safe as is however is fast to catch fire considering it is made from paper. Fire resistant chemicals are mixed with the shredded papers in the manufacturing process to eliminate the risk of catching fire during the life span of the installation. Perlite is natural rock material that is low in thermal conductivity. The Rock is crushed to smaller form and used inside cement and brick as shown in Figure 4 walls to enhance the insulation of the building.

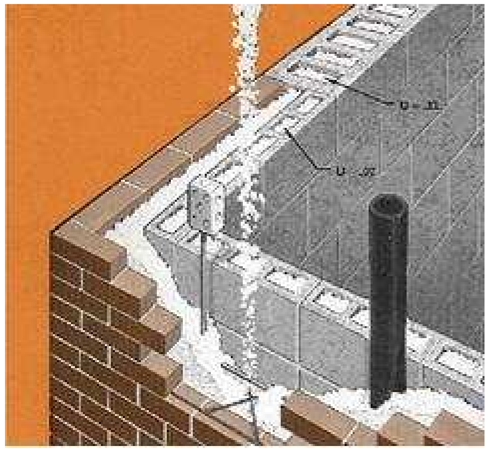

Figure 4: Perlite is installed in cement and brick walls [21]

State-of-Art Materials

Aerogel

Aerogel is one of the top promising technologies in thermal insulation area [22]. Aerogel is made up of a gel that has had its liquid component replaced with air; in fact the material is 99% air. It’s quite thin, breathable, and fireproof, doesn’t absorb water, and is very strong considering its weigh. Aerogel has a very low thermal conductivity of (14 mW/m-K) which results in an R-Value that is twice better than what other typical insulation provide [7]. Aerogel is fairly expensive compared to traditional insulation materials and out of the price range for the average homeowner. It is a great material for insulation where size matters [22]. Only Two companies currently have a commercial product available – Aspen Aerogel and Thermoblok. Aerogel has been used before in insulation for a number of NASA projects including the Mars Rover and space suites [23]. There are many applications for aerogel beside insulation like super insulating blankets which made with aerogel. They are also the world’s lightest solid materials, and mechanically robust aerogels [24].

Vacuum insolation panels (VIP)

Vacuum insulation panels are one of the more efficient materials compared to other alternatives because of its low thermal conductivity (3-4 mW/mK) [7]. In the structure of this insulation, open porous material will be enveloped by thick metal sheets or materialize polymeric layers to act as a barrier for environment and handling protection. The materials that are used as a porous core need to have suitable pore size in order to maintain the vacuum. The core materials can be foam, powder, fiber, and fiber/powder composites such as polyurethane, expanded polystyrene, silica, and expanded perlite [25]. Then, gaseous heat transfer is suppressed to the core materials. Despite the very low thermal conductivity that helps in reducing the thickness, the installation process and application type need to be considered because it is the most critical aspect of this material. Even though VIP has very low thermal conductivity, it tends to increase easier than other state-of-art material over time. Moreover, handling and maintaining this material needs to be very cautious because the vacuum can be lost, and thermal conductivity will be increased. Another drawback of this material is that it cannot be cut to adapt and adjust the shape at construction site because cutting will result in losing the vacuum [7].

Gas-filled panels (GFP)

The technology and functioning of Gas-filled Panel is similar to the Vacuum Insulated Panels. The core of the panel is created by a baffle structure which is filled with a gas with a lower thermal conductivity than air [7], such as Argon (Ar), Krypton (Kr) or Xenon (Xe). The whole structure of GFPs is very fragile so all process from handling to applying it to walls must be carried out with high caution. GFPs are still in a research state and first prototypes are not able to reach the theoretically calculated low thermal performance which was expected [26]. They show similar advantages and disadvantages than VIPs but are not able to reach the thermal performance and they are more expensive because of the gas that is included in the GFPs [26].

Phase change material (PCM)

Phase change materials (PCM) are able to absorb heat and release it as temperature changes [27]. This absorbing and releasing of temperature is not a unique characteristic of these materials. What makes it unique is the sensitivity of the material to the surrounding temperature changes and the ability to store the heat. PCM change material state from solid to liquid when it absorbs the heat as shown in Figure 5. The PCM will maintain the liquid status until temperature drops causing the heat to be released. As the heat is released the PCM will return to its sold state.

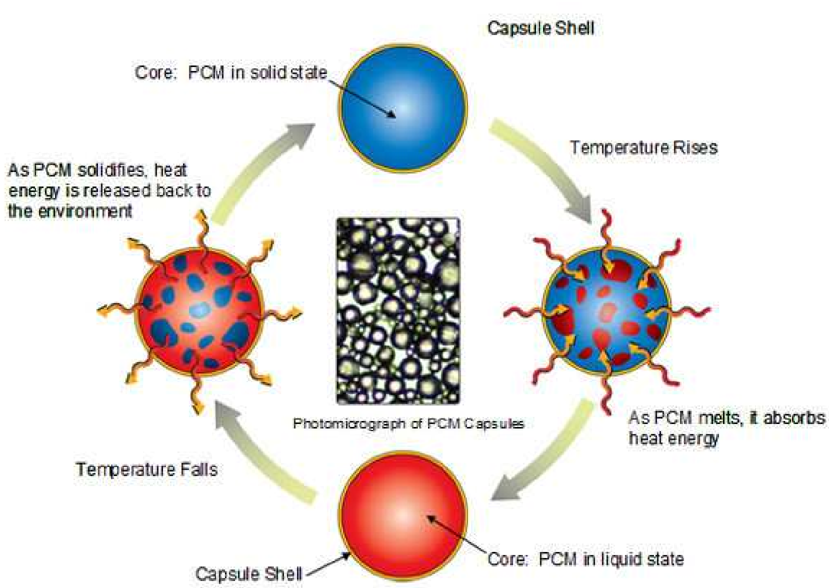

Figure 5: Phase Change Material technology [27]

Because of the way PCM store the heat, PCM is very promising for heat storage technologies. Currently PCM is used in construction as insulation improvement in building materials in concrete mixes or bricks. PCM can also be mixed in Wool or fiber batts insulations to improve on their thermal insulation performance. Because PCM is used as an additive or part of a concrete mix and not used in a standalone format, this added difficulty in evaluating this product against the rest of the insulation materials studied in this report.

Scoring model

The first step in the assessment of construction insulation technologies and materials was the definition of the assessment criteria. These criteria will be the same for the scoring and the HDM. This will enable the study to both evaluate the actual available technologies and identify further research areas for the state-of-the-art technologies to become competitive or superior to the most used insulation materials so far. The definition of the criteria is based on an extensive literature review about needs and features of construction insulation by applying a multiple perspective approach described earlier. The criteria are described on the following section.

Technical criteria:

- Thermal performance: This is mainly based on the thermal conductivity expressed in the unit W/mK. It can be interpreted as the ability of a material to transfer and transport thermal energy through the material. The smaller the thermal conductivity of the material the better is its insulation performance. For insulation materials, the reciprocal value of the thermal conductivity, the R-value, is commonly used [28].
- Cost: This criterion only includes the one-time purchase and installation cost. There is no evaluation of life-cycle cost. The scoring is mainly based on the cost per R-value of a material and a comparison of prices for the same insulation thickness.
- Durability: It is to evaluate the time impact on insulation material, e.g. the behavior of the R-value over time, water and moisture effects, thermal expansion and contraction, settling over time, etc.
- Ease of construction: This criterion is to evaluate the impact of insulation material/technology on workmanship requirements, ease and speed of construction, ease of operation, maintenance and replacement.

Environmental criteria:

- Life-time impact: The negative environmental impacts caused during the production and usage is considered in this criterion. This includes the used ingredients of the insulation material as well as potential toxic and hazardous products which could outgas during the life-time.
- Recycle impact: This criterion covers the easiness and possibilities to recycle or dispose the insulation materials.

Organizational criteria:

- Availability: We will evaluate the market availability in this criterion. Assessment criteria are the easiness to purchase the material, the number of companies which manufacture it, the distribution channels, etc.
- Building code requirements: The fulfillment of the legal requirements and government specifications will be evaluated with this criterion.

This assessment paper uses a scoring model to assess and compare all the introduced and described construction insulation technologies and materials. The scoring model uses values from 1 to 4 with 1 being the worst and 4 being the best score. We are aware of the fact that scoring with only four values can distort the results of quantitative criteria like the thermal performance or cost but we intentionally used the same scoring range for every criterion to simplify the interpretations of the scoring results. The scoring is based on a literature review about the capabilities of the different materials, the advantages and disadvantages of the technologies in general and each material itself as well as the potential issues related with each material.

The results of the scoring are presented in the following paragraphs. The scores for each criterion will be showed in a separate chart. The scores of the traditional materials are in blue color and the state-of-the-art technologies are colored in green. The first evaluation criterion is the thermal performance. We looked at the range of all evaluated thermal conductivities for every material and calculated the scores based on these values. Some insulation materials can be produced and manufactured in different ways or special treatments or add-ons can slightly influence the thermal conductivity of insulation materials. That is why we calculated the average of all values found for each specific material. A perlite rigid board has the worst average thermal conductivity of 0.05 W/mK [12], whereas VIP has the best with 0.004 W/mK [7]. Again, the smaller the thermal conductivity, the better the insulation affects. The difference between the worst and the best value is 0.046 W/mK which leads in the score system to a single score size of 0.0115 W/mK.

$$\frac{0.046}{4} = 0.0115$$

Based on this calculation, each material can be scored in the following scheme:

Table 4: Scoring scale calculation

score	thermal conductivity [W/mK]
4	0.004 – 0.0155
3	0.0155 – 0.027
2	0.027 – 0.0385
1	0.0385 – 0.05

The scoring shows, Figure 6, that aerogel and VIP are the only two products with a score of 4 in matters of thermal performance. All foam materials, extruded polystyrene boards and ISO boards, as well as cotton batts and fiber-glass loose fill have a score of 3. It is interesting that fiber-glass batts have a different score than fiber-glass as loose fill. The open cell structure of fiber-glass used in loose fill insulation results in a lower thermal conductivity [12]. So even in terms of thermal performance, the same material used as a different insulation technology can influence the scoring. This is also the case in other criteria as we can see later. PCM insulation is not scored because there is no single insulation only consisting of PCM and the material characteristics are strongly changing due to the ability of changing phases within the material. If PCM is used as a thermal insulation it is always combined with other insulation material and the thermal conductivity is mainly dependent on the other insulation [29].

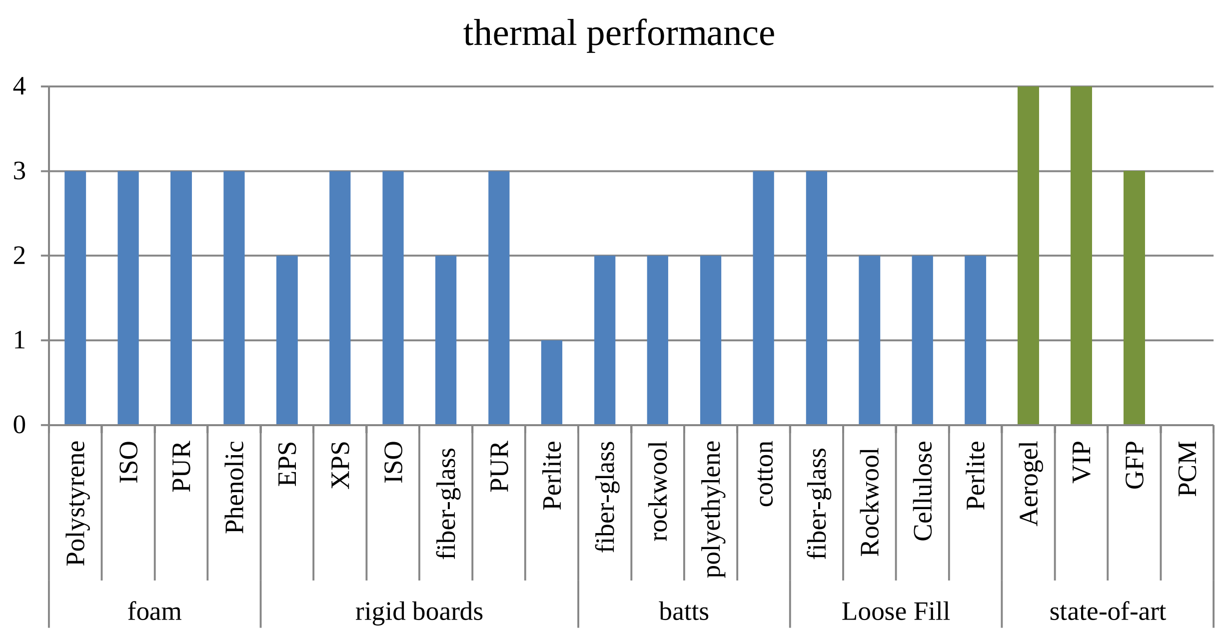

Figure 6:Scoring results of the thermal performance critiria

The scoring results of the cost criterion, Figure 7, are based on price comparison between the different materials as well as the information found in research paper. The following chart shows the result of the cost scoring.

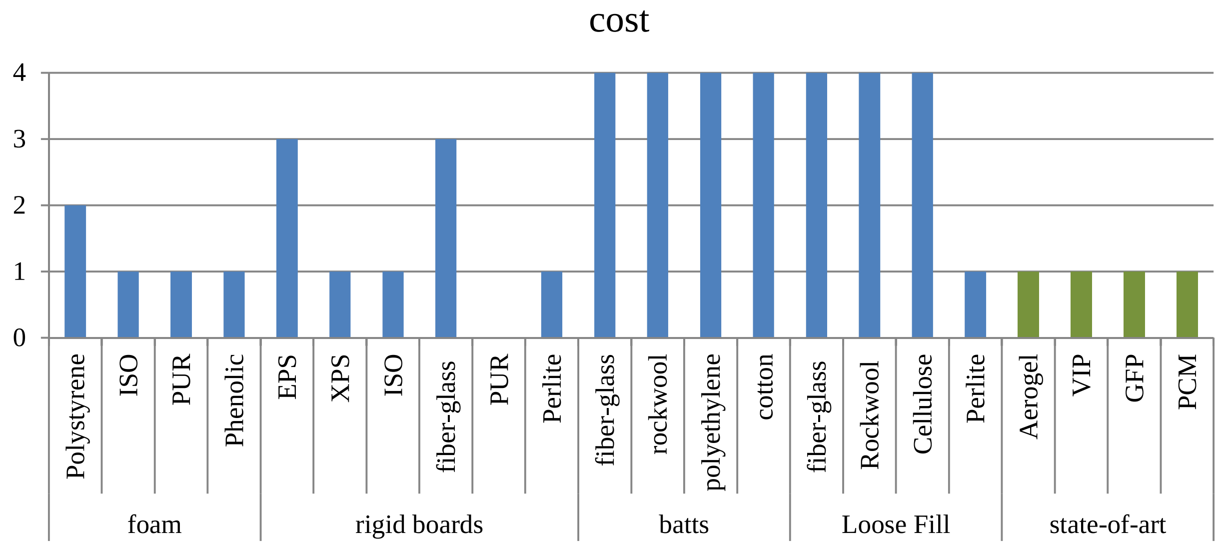

Figure 7: Scoring results of the cost criteria

Except of perlite loose fill, all loose fill and batt insulation are the cheapest insulation materials. Rigid boards and foam are more expensive and all state-of-the-art insulation technologies are more expensive than the traditional ones and they are all scored with the worst score of 1 [12]. Even in terms of a comparison of the costs per R-value, where the advanced materials could benefit from because there is less material needed to achieve the same R-value, the state-of-the-art technologies are still the most expensive ones [12]. So including their better thermal performance in the cost evaluation does not result in higher scores for the new technologies.

The durability defines the long term behavior of the materials. Aerogel and Perlite are showing, Figure 8, no aging effects and are scored with 4 points [12]. The thermal performance of cotton, fiber-glass and Rockwool can be reduced through moisture or increasing compression because of settlement [6]. All the other traditional materials are affected by a decreasing R-value over time [12]. VIP and GFP show a slow loss of vacuum and gas respectively. They can be easily damaged either at the construction site or later by drilling holes or putting nails in the walls [7]. That is why VIP and GFP are scored with worst.

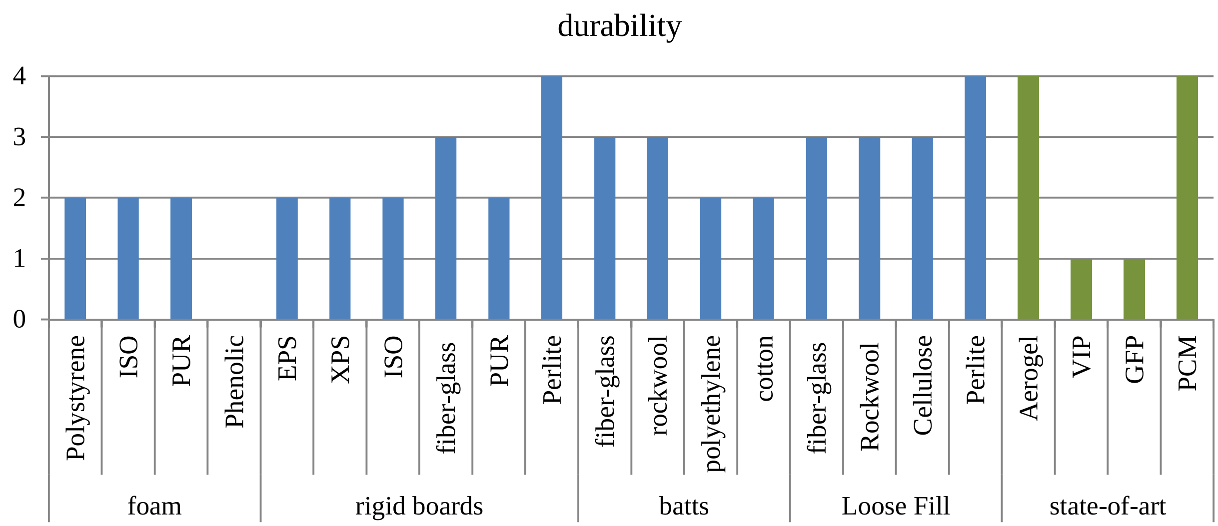

Figure 8: Scoring results of the durability criteria

The next evaluation criterion is the easiness of construction, Figure 9. The insulation technologies show greater differences compared to the other technologies than the materials in its respective technology. The easiness of construction is more depending on the shape and the structure than on the material itself. It is for example a big difference if the insulation is brought to the construction site as liquids and the foam is expanded directly in the wall or if the pre-manufactured foam board needs to be put on the wall. This is why all the foam materials and batts have the same score and all rigid boards and loose fill are scored similar as well.

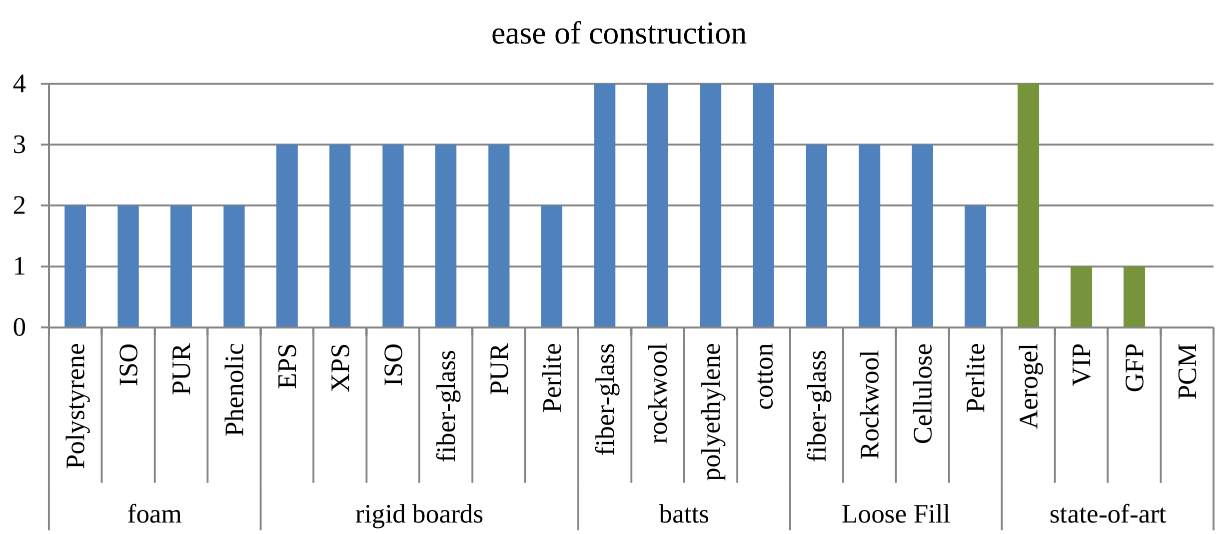

Figure 9: Scoring results of the ease of construction criteria

All insulation materials that are formed as batts are easy and convenient to install [15]. They all qualify for DIY and they need no curing or drying time so the resulted installation time is also short [30]. All

Rigid boards and loose fill, except Perlite, are scored with 3 points. Rigid boards are easily cuttable and adjustable on the construction site and there is no special equipment needed to install it [12]. Loose fill materials are very easy for attic insulation and these loose materials are well suited for places where it is difficult to install other insulations [6]. Foam insulation fit in all cavities because they are sprayed or filled as a liquid into the walls and the foam expands afterwards. However, this advantage is equalized by the need of special equipment and professional installers. It also needs drying time and the quality and the thickness of the insulation can hardly be controlled, so all foam insulation get 2 points. Aerogel for wall insulation is produced in a similar shape and form than batts and it is installed in the same way [31]. It has also the widest range of different thermal insulation applications and is therefore scored with 4 points. VIP and GFP are absolutely not adjustable at the construction site and the large pre-manufactured panels need professional installation workers [32]. That is why we scored them with the worst score for ease of construction.

The next two scoring criteria are evaluating the environmental perspective of the insulation technologies and materials. As explained above this perspective is divided in the environmental impacts during the life-time, Figure 10, and after the usage of it by looking at the recycle, Figure 11, and dispose issues. All materials that are scored with 4 points are showing no special negative environmental impacts both for manufacturing them and during the usage as an insulation material. The polystyrene materials include a toxic brominated flame retarder and either CO_2 or HCFC is used as an expanding agent [12]. GFPs are filled with toxic noble gases and are therefore scored with only two points [7].

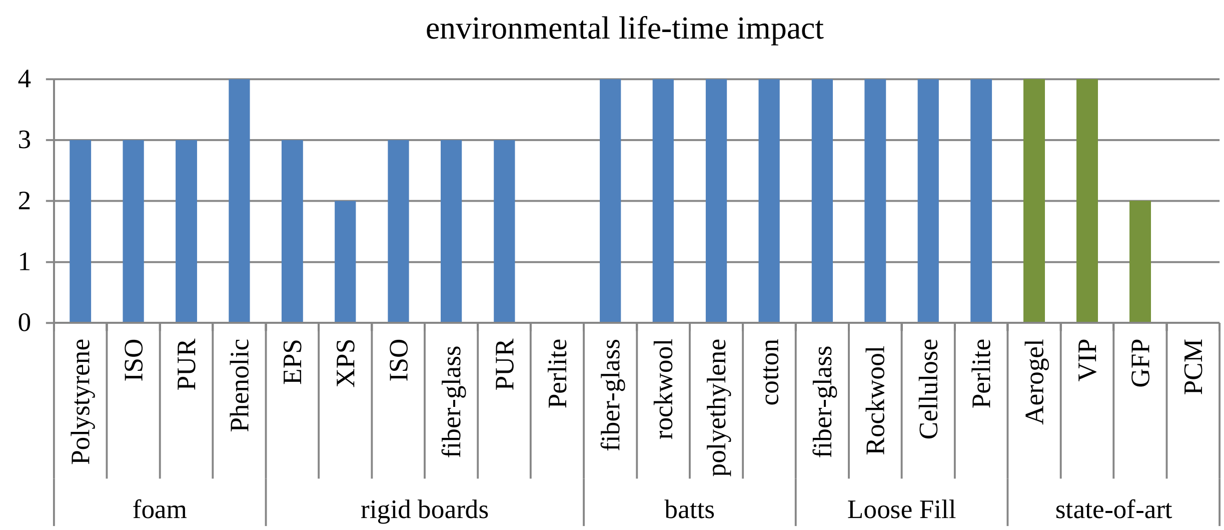

Figure 10: Scoring results of the environmental life-time impact criteria

The negative recycle and dispose impacts are based on a similar scoring like the criterion above. Having 4 points means no special negative impact and easily disposable or even recyclable. This is only the case for Perlite, Aerogel and VIP [7]. Fiber-glass, Rockwool, cotton and cellulose insulations can normally disposed, too without big impacts on the environment [33]. The fire retarders are causing special treatment before disposing and this is why all flammable materials that include fire retarders are scored with only 2 points. However, there is no material which is absolutely not disposable or recyclable, so no material is scored with 1 point.

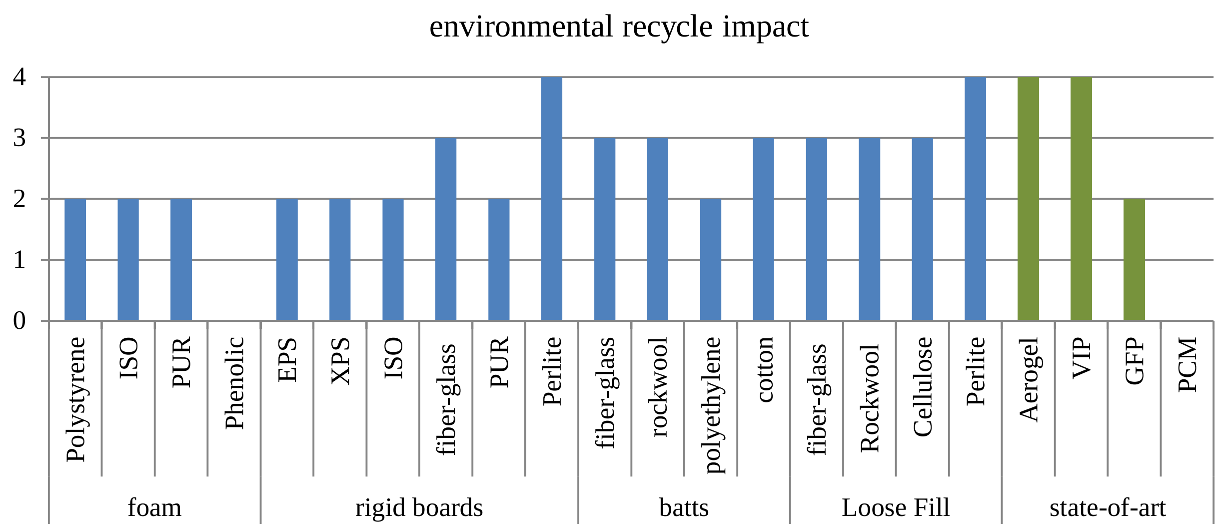

Figure 11: Scoring results of the environmental recycle impact criteria

The last two criteria are evaluating the insulation materials more from an organizational perspective. The availability, Figure 12, looks at the easiness of purchasing the materials and the different sources to order and purchase the insulation.

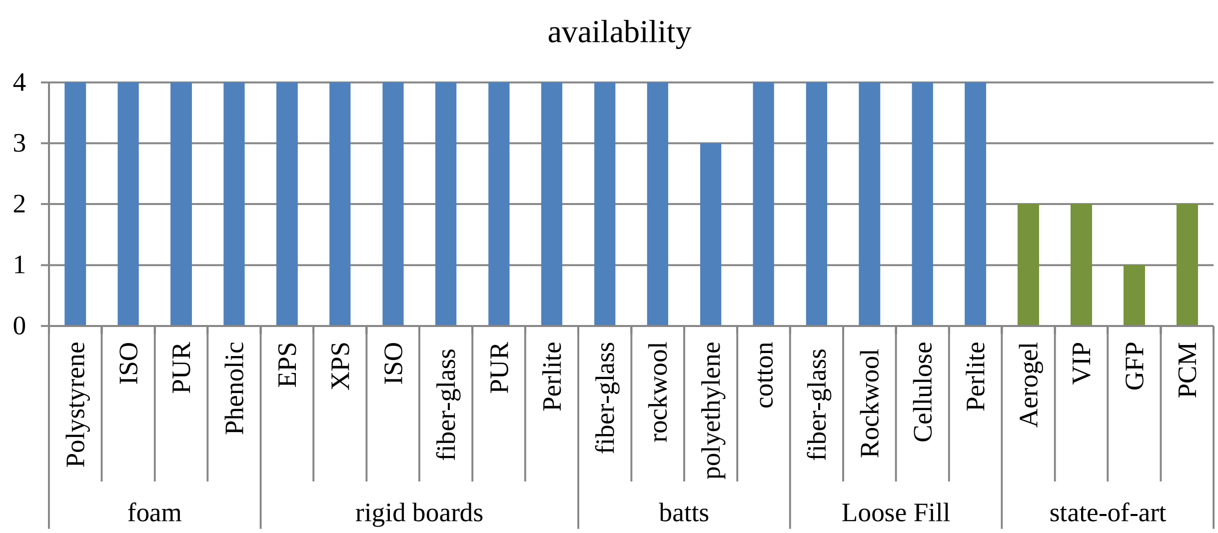

Figure 12: Scoring results of the availability criteria

Except of polyethylene batts, which require special order, all traditional materials are scored with 4 points because there are many companies which manufacture or trade with these materials and most of them can be purchased in building centers. This is pretty different with the state-of-the-art materials. There are only few companies which are offering these products and often times it also needs special construction companies that are able to use these technologies [34]. With GFP materials we were not able to find one company that offers GFP and it seems that this technology has not left the research state yet.

The last assessment criterion is the building code requirements, Figure 13. The scoring in here is based on the fulfillment of the legal instructions and obligations. Phenolic, Perlite, Rockwool and VIP are scored highest because these materials are all causing no skin and/or odor irritations as well as they are all free of health hazardous ingredients and they are also the most fire-resistant materials [12]. All other traditional materials are less fire resistant but are still good in all terms of health concerns and irritations. There are no legal restrictions known for Aerogel and VIP as well so they got the best score in here, too [7].

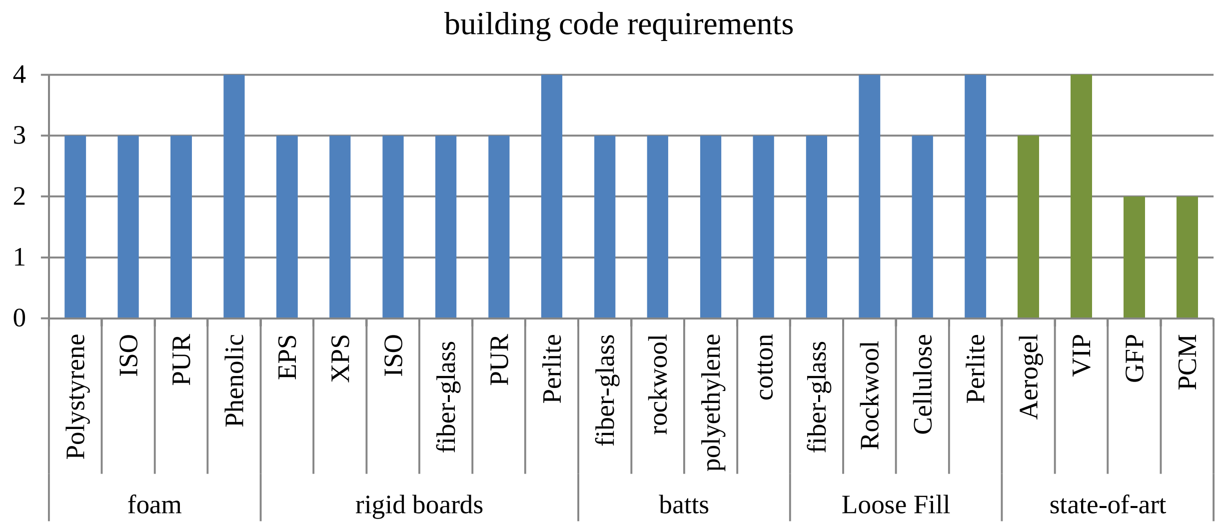

Figure 13: Scoring results of the building code requirements criteria

The scoring of the materials is complete and the next chapter will introduce our used HDM and show the results of the different experts.

Hierarchical Decision Model

HDM tool has been used to collect expert input on prioritizing the insulation technologies in construction sector. The decision is to find the insulation technology alternatives that have the highest potential contribution to overall objectives and goals of energy saving. In this section we will emphasize on what the HDM outcome communicated to the project objective and criticize the inconsistencies and disagreements of the expert judgments by highlighting their effect on the final result. In this section all the data are collected and analyzed toward the final assessment. The evaluation of thermal insulation technologies included wide range of variables which has been identified by the researcher based on literature review. The HDM was developed and validated in multiple iterations before it was before it was finalized for submission to the identified experts. The team has contacted 16 experts in the field of construction insulation by email. The e-mail included the HDM link to access the model, a brief explanation of our study purpose and expectations. Three experts replied by quantifying the HDM model based on their knowledge and experience in the field. The different criteria at all levels of the HDM clearly described within the model to define each of these terms and clarify the sub-aspect entailed in each term. One of the major strengths of the HDM is the use of pairwise comparisons to highlight accurate ratio scale priorities, as opposed to using traditional approaches of assigning weights which is difficult to justify. In this scenario a Hierarchical Decision Model (HDM) has been delivered to evaluate the insulation quality criteria which are divided to three different aspects (Technical, Environmental, and Organizational) .The model was developed to examine the contribution of various insulation technology criteria to the mission of selecting the most important insulation features. The following is a graphical presentation of our HDM model, Figure 14.

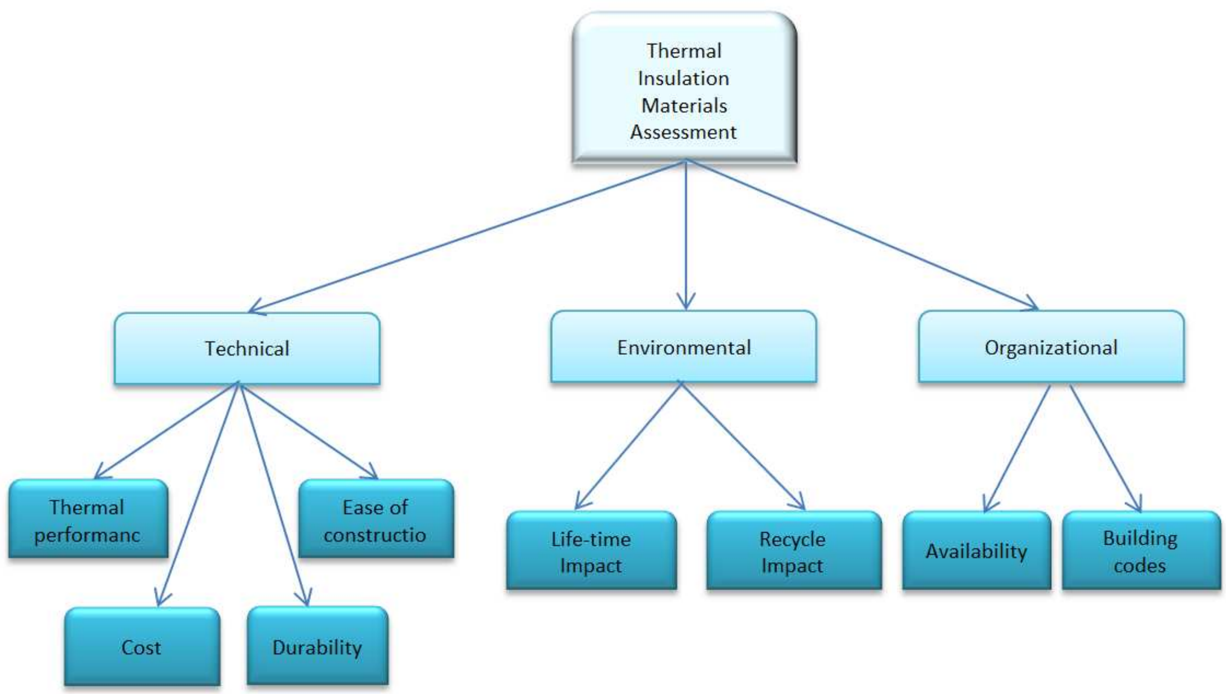

Figure 14: Hierarchical Decision Model

Typical hierarchical decision model (HDM) methods use the ***mean*** values to aggregate the opinions of the experts. The results will weight criteria respect to each criterion. Other indictors to be considered in HDM analysis are the inconsistency and the disagreement rates. Inconsistency in the judgment is defined as the mean of the population standard deviation of each expert in each decision element. A conservative limit for acceptable Inconsistency is 0.01. Disagreement is the rate of difference in viewpoint among experts. The disagreement in the group's subjective judgments is calculated using the value assigned to each decision element and the mean of responses. A conservative limit for acceptable Disagreement is 0.1.

For the purpose of this model each expert has quantified a certain level of the Hierarchical model that fits the best to their expertise area. Expert 1 and Expert 3 have quantified the third level of the model, while Expert 2 has quantified the second level. The following is a graphical presentation of individual experts' judgment

Expert 1: Figure 15, this expert evaluated at the third level. The pairwise comparison data for the Technical criteria was shows that cost got the highest at 0.36 followed by durability at 0.26. Ease of construction and thermal performance got 0.22 and 0.16 respectively. In the environmental criteria, life-time impact received 0.60 and Recycle impact received 0.40. Last, in the Organizational criteria, availability received 0.30 and building code requirement received 0.70

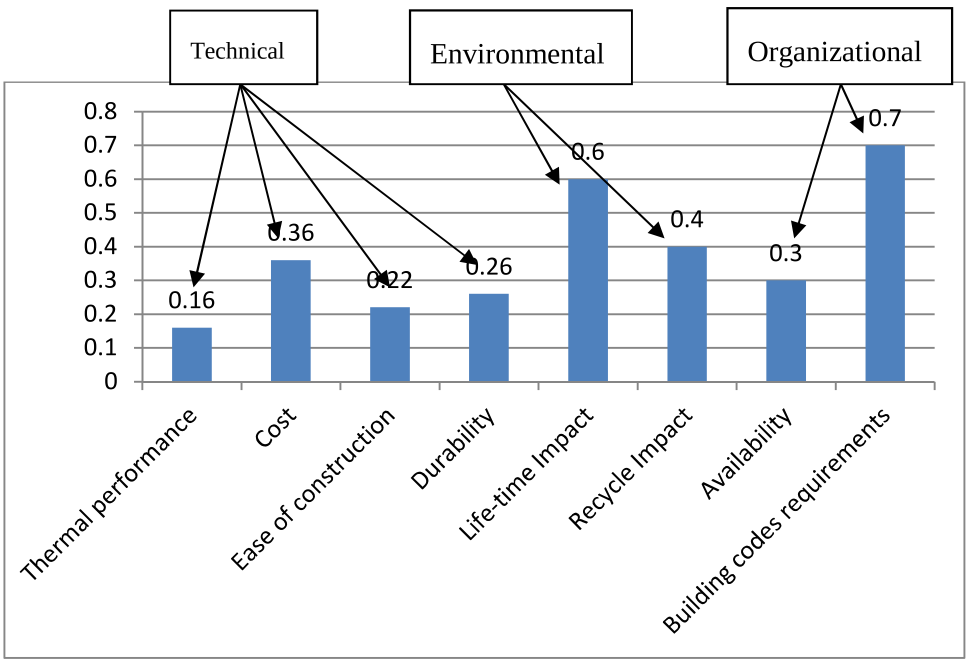

Figure 15: Data captured from Expert 1

Expert 2: like expert 1, this expert, Figure 16, judgment contributed to the second level of the model where the researcher attempt to identify the three perspectives (Technical, Environmental, Organizational) to which the different insulation technology criteria are categorized. It's noticeable from the figure below that this expert has raised the importance of technical aspect above the other two perspectives. In his opinion Environmental perspective participates the least in making decision when choosing insulation. Expert 2 result has a level of 0.02 inconsistencies.

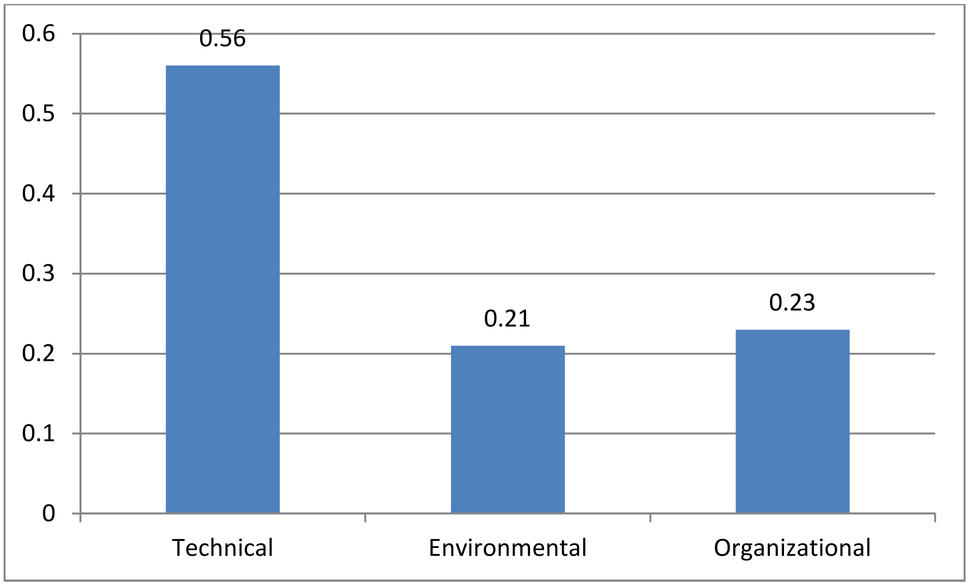

Figure 16: Data captured from Expert 2

Expert 3: Figure 17, like expert 1, this expert evaluated at the third level. The pairwise comparison data for the Technical criteria was shows that thermal performance and durability received 0.37 equally. Cost and Ease of construction got 0.16 and 0.09 respectively. In the environmental criteria, life-time impact and Recycle impact received 0.50 each. Similarly, in the Organizational criteria, availability and building code requirement received 0.50 each

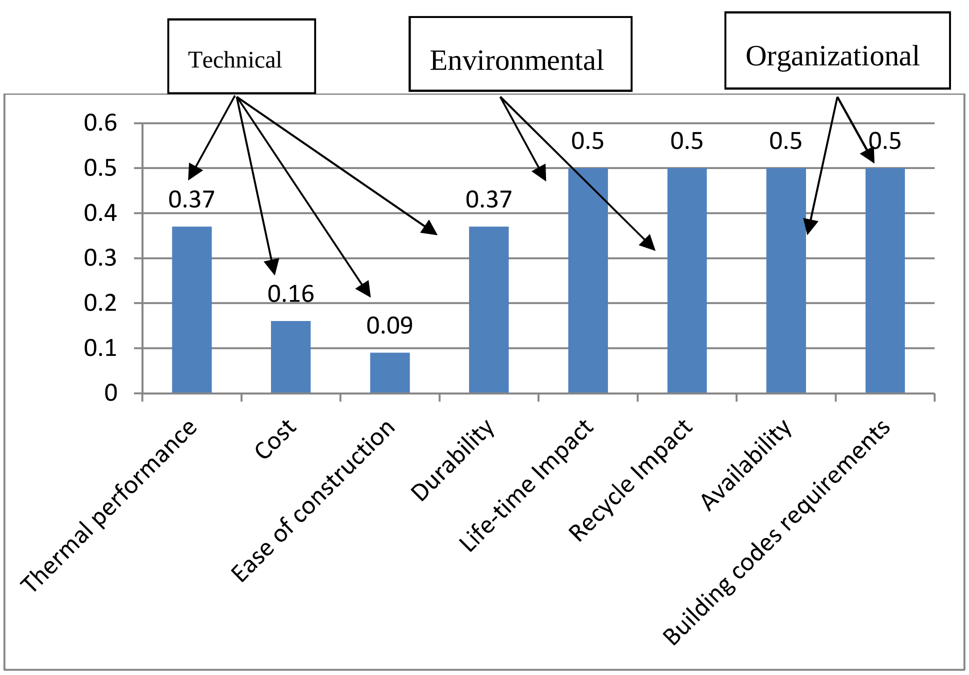

Figure 17: Data captured from Expert 3

Analysis & Discussion

The presentation of the used methodology to assess thermal insulation technologies were mainly focused on the introduced criteria. The scoring results were showed separately for each criteria and the HDM helped to find the weight and the importance of the criteria. The following analysis of the scoring results will focus more on the insulation technologies and materials and it will combine the scoring results with the HDM data. The performance analysis of the state-of-the-art technologies is only focused on aerogel and VIP. VIP and GFP are pretty similar technologies and the scoring showed that VIP is superior to GFP. So we decided to exclude GFP of the further analysis. This is also supported by literature resources who argument in the same direction that future research should focus more on VIP than on GFP [7]. The technology of phase change materials is not included because PCM is not possible stand-alone insulation material. It has to be included in other insulation or construction material to be used as house insulation. So it is not completely matched to all the other technologies and materials and a comparison would lead to biased results.

To analyze the strengths and weaknesses of the state-of-the-art technologies they are compared with the traditional materials. There are criteria where Aerogel and VIP are scored better and there are others were the majority of the traditional materials perform better but most of the criteria show indifferent scores with no clear trend against or in favor of the use of state-of-the-art technologies. The following chart, Figure 18, displays the scoring results for Aerogel and VIP as well as extruded Polystyrene (XPS) and fiber-glass loose fill as two wide used insulation methods.

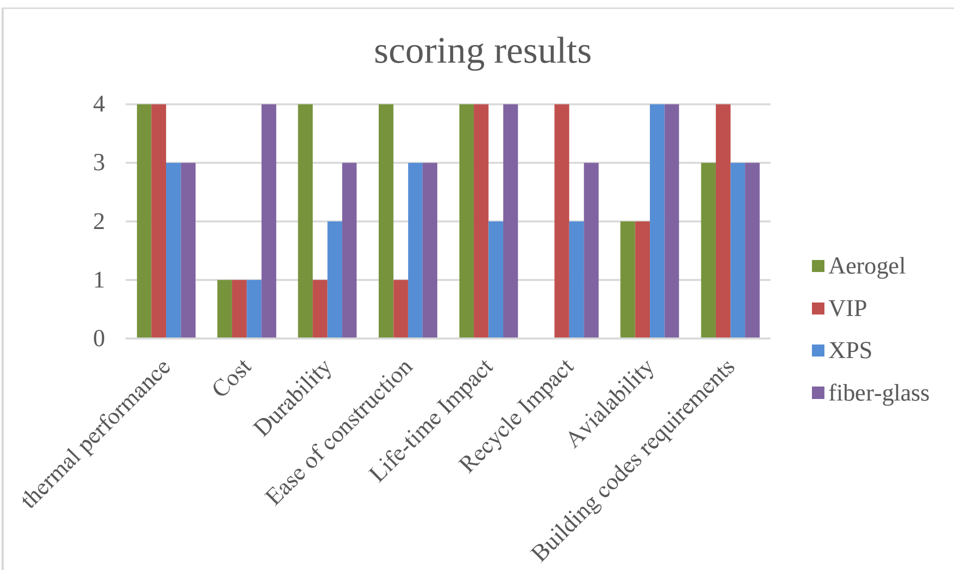

Figure 18: Scoring results; comparing top 2 State-of-the-art with 2 wide used traditional materials

The scoring table shows that Aerogel and VIP are superior in thermal performance and they both are scored best in the environmental criteria. The weaknesses of the two state-of-the-art technologies are the availability and especially the cost criterion. The following HDM result analysis highlights the most important criteria to re-evaluate Aerogel and VIP with regard to the most important categories. This will help to define areas on which future research about Aerogel and VIP have to focus in order to be comparative or generally superior to the traditional types.

After collecting the inputs from the three experts, the team had to examine the validity of the result by observing the inconsistency and the disagreement level to make sure they are within the acceptable level. Although Expert 2 and Expert 3 have 0.02, 0.03 inconsistency in their judgment, the overall inconsistency level was within the limit for HDM restrictions, so there was no need to re-contact any of the expert for a revision. Disagreement of 0.00 was calculated among the three experts opinion. Two of the experts were highly agreed with each other in term of their preferable among model variables. While the third expert has slightly differentiated his input in term of what he think is the important consideration for selecting insulation technology. Although, the disagreement was within the acceptable level for HDM, the team tried to inspect the reason of the different evaluation among experts. The conclusion was that experts grounded their judgment by their own background. However combining the three experts input reflect more powerful result that beyond the individual preference. The composite input of the three experts is presented in the following chart, Figure 19.

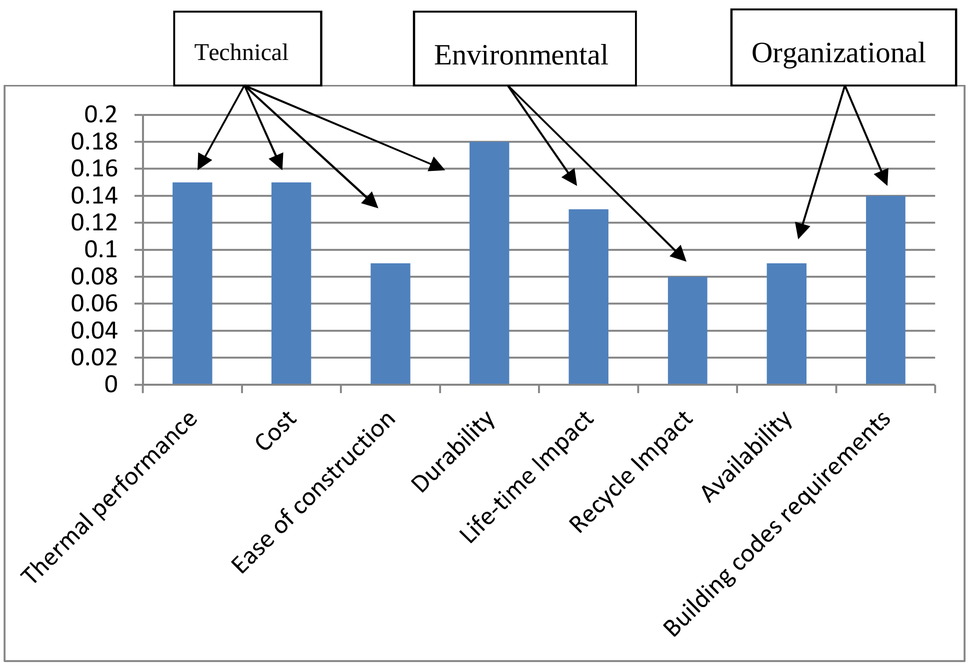

Figure 19: HDM results (mean values)

Durability of the insulation technology and material has been emphasized the most in the composite result of the three expert inputs. While both Cost and Thermal Performance came at the second place. The three criteria mentioned are technical aspect of insulation technology. However the criteria that came at the third place in the composite result was the Building Code Requirement which is categorized under the Organizational perspective. Although one of the experts evaluated the criteria under environmental aspect as the most important among all others, none of the environmental criteria took place within the top three.

At this point of the study, the researchers were able to identify the available insulation technology and material and to present them in the Technology land-Scape model. As was presented in the landscape analysis section, the materials were categorized in two sections, traditional and state of art. Where traditional include all existing insulation for construction in today market, while the state of art included the insulation technology that still in developing phase under R&D lab. Using literature review, scoring model and expert opinion, the team were able to recognize the most two promising insulation technology from the state of art category as mention above. Considering HDM outcome, Table 5: Scoring results of top 5 criteria per expert judgment from HDM results, Aerogel and VIP occur to score highly at four out of the top five criteria according to expert judgment. However, the two of them scored very low from cost perspective, one of the top five important criteria. The following table shows the scores which Aerogel and VIP accomplish for thermal performance, cost, durability, life-time impact and building code requirement.

Table 5: Scoring results of top 5 criteria per expert judgment from HDM results

Top 5 Criteria	Aerogel	VIP	XPS	Fiber-glass (loose fill)
Thermal performance	4	4	3	3
Cost	1	1	1	4
Durability	4	1	2	3
Life Time impact	4	4	2	4
Building Code Requirement	3	4	3	3

After analyzing the results of the scoring and the HDM, the next section will include research conclusions and recommendations for further R&D.

Conclusion & Recommendation

After the project objective was selected, the methodology for assessing insulation technologies and materials were performed. Starting with a gap analysis, it is used to identify the direction for future advanced insulation technologies. After that a landscape analysis was conducted to categorize the insulation materials which are already in the market and in a promising research phase for future applications. These two major groups of insulation materials were identified, traditional and state-of-the-art technologies. Further improvements for the state-of-the-art technologies at the conclusion of this research are recommended. These improvements will better place the state-of-the-art products in the market to compete with traditional ones in the home construction field. Therefore, two methods were used in parallel to assess the capabilities of all thermal insulation materials. One is scoring the insulation technologies based on the literature review. Then, it is followed with creating Hierarchical Decision Model (HDM) based on expert judgments in each evaluation criteria that are the same as in scoring method.

From the result, the authors conclude that Aerogel will be the most promising insulation material for future use with the highest score in 4 out of 5 important criteria; Durability, Life-time impact, Recycle impact and Building Code requirement. However, the analysis shows that cost is high for the state-of-the-art materials to compete with the traditional materials. Aerogel scored very low in this area even though this cost criterion is identified as important by the expert judgments. Similarly, VIP which scored better in environmental area, but the cost is the weakness of this technology. Both materials receive better score in thermal performance when compared with traditional technologies. However, the high cost of Aerogel and VIP are preventing them from further diffusion in the construction insulation market. Because of the cost factor, traditional technologies still have the advantage to be used in construction today.

Recommendations after assessing and analyzing construction insulation materials are for research and development to focus on reducing cost for the state-of-the-art materials. The main focus should be to improve manufacturing processes to lower the production costs especially for Aerogel and VIP. Both Aerogel and VIP proved to perform high as an insulation material. Improving the manufacturing process will help to reduce the production cost leading to better marketability and to become superior construction insulation materials. Further process innovations needed for these to technologies to establish cost-effective mass production procedures.

The large panel size of VIP and GFP as well as the challenge and experience needed to install them at the construction site are big disadvantages compared to other available insulation materials. This disadvantage requires R&D to improve ease of construction for VIP and GFP. As the study shown, these two products are hard to customize for installation on site because of potential gas or air leakage. Further R&D can focus on flexibility of these products for use in the construction field by the installer.

In addition if government and regulations gave higher incentives for the higher performance insulation materials, the state-of-art materials will have a greater advantage over the traditional materials. This will help these technologies to be widely used and be more available to the market.

The analysis in this report is useful for R&D in the insulation industry. The HDM results highlighted the critical criteria chosen by experts when selecting an insulation material. The landscape analysis and scoring results in this report can be used for homeowners and construction companies to choose their preferred insulation material for their specific need.

Future Research

The authors suggest areas for future research and studies in assessment of insulation materials.

Future Research

- Further research to asses insulation materials using other Methodologies
- Further research for additional government incentives
- Further research to include life cycle cost calculations
- Comparison of market diffusion of other construction technologies and materials

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Appendix

Scoring table of Foam Materials

	category	traditional			
	type	**foam**			
	materials	**polystyrene**	**polyisocyanurate**	**PUR**	**phenolic**
Thermal performance	min thermal conductivity	0.033	0.02	0.02	0.02
	max thermal conductivity		0.028	0.038	0.025
	average	0.033	0.024	0.029	0.0225
	score	3	3	3	3
Cost	cost per R-value [13]		high	high	
	price per sq. ft for 1 inch thick				
	score		1	1	
Durability	[13]	R-value decrease with time	R-value decrease with time	R-value decrease with time	
	score	2	2	2	
Ease of construction	advantages	fills in all cavities; possible solution for existing buildings without wall insulation	fills in all cavities;	fills in all cavities;	fills in all cavities;
	disadvantages	needs drying time; needs professional installer: cannot control thickness; hard to control quality;	needs drying time; needs professional installer: cannot control thickness; hard to control quality;	needs drying time; needs professional installer: cannot control thickness; hard to control quality;	needs drying time; needs professional installer: cannot control thickness; hard to control quality;
	score	2	2	2	2
Life-time Impact		includes brominated flame retardant HBCD (toxic) (hexabromocyclododecane) (included in all polystyrene insulations)			
	score	3	3	3	4

Appendix

Recycle Impact		[27]	[27]	[27]	
	score	2	2	2	
Avialability					
	score	4	4	4	4
Building codes requirements	Fire resistance [13]				
	Fire resistance				
	Health Hazardous				
	Odor/skin irritation				
	score	3	3	3	4

Appendix

Scoring table of Rigid boards Materials

	category	traditional					
	type	**rigid boards**					
	materials	**EPS**	**XPS**	**Polyisocyanurate**	**Fiber-glass rigid board**	**PUR boards**	**Perlite**
Thermal performance	min thermal conductivity	0.029	0.025	0.023	0.032	0.02	0.04
	max thermal conductivity	0.045	0.037		0.063	0.03	0.06
	average	0.037	0.031	0.023	0.0475	0.025	0.05
	score	2	3	3	2	3	1
Cost	cost per R-value [13]	lowest for rigid board types	high	high	medium		high
	price per sq. ft for 1 inch thick	0.19	0.42	0.7			
	score	3	1	1	3		1
Durability	[13]	R-value decrease with time	R-value decrease with time	R-value decrease with time	better durability than fiber-glass batts	R-value decrease with time	high
	score	2	2	2	3	2	4
Ease of construction	advantages	easily cutable and adjustable on construction site	easily cutable and adjustable on construction site	cutable, but more difficult than polystyrene	easily cutable and adjustable on construction site	easily cutable and adjustable on construction site	
	disadvantages	fragile	fragile				
	score	3	3	3	3	3	2
Life-time Impact		uses pentane gas as the expanding agent, toxic; includes brominated flame retardant HBCD (toxic) (hexabromocyclododecane) (included in all polystyrene insulations); • Environmental rating: A+ (best)	uses HCFC or CFC gases as the expanding agent, toxic fumes; • Environmental rating: with HFC: E (worst)	uses CO2 or CFC gases as the expanding agent, toxic fumes	Quite safe, may be some out-gassing of resins used as binders	serious health concerns and hazards in case of a fire	
	score	3	2	3	3	3	0

Appendix

Recycle Impact		[27]	[27]	[27]		[27]	
	score	2	2	2	3	2	4
Avialability							
	score	4	4	4	4	4	4
Building codes requirements	Fire resistance [13]						
	Fire resistance						
	Health Hazardous						
	Odor/skin irritation						
	score	3	3	3	3	3	4

Appendix

Scoring table of batts Materials

	category	traditional			
	type	**batts**			
	materials	**fiber-glass**	**rockwool**	**polyethylene**	**cotton**
Thermal performance	min thermal conductivity	0.033	0.037	0.041	0.029
	max thermal conductivity	0.04			
	average	0.0365	0.037	0.041	0.029
	score	2	2	2	3
Cost	cost per R-value [13]	low	low	low	low
	price per sq. ft for 1 inch thick	0.055 - 0.085			0.0625 - 0.09775
	score	4	4	4	4
Durability	[13]	compression reduces R-value	compression reduces R-value	R-value decrease with time	R-value can change over time: can be significantly lower due to typically deficient installation
	score	3	3	2	2
Ease of construction	advantages	Fitted between studs, joists or rafters[15], No settling, No dry time require [4]; easy to replace	Fitted between studs, joists or rafters[15]		No settling, No drying time require, DIY but need motorized cutting tool [4]
	disadvantages	protection glasses and gloves required for cutting	protection glasses and gloves required for cutting	difficult to handle and cut with standard tools	must be properly fitted to completely fill the wall without being compressed by pipes or wires
	score	4	4	4	4
Life-time Impact		4.5	4.5	made from recycled plastic milk bottles	0.5
	score	4	4	4	4

Appendix

Recycle Impact		recycle content [24]	recycle content [24]	hard to dispose because of fire retarders	be recycled or composed
	score	3	3	2	3
Avialability				special order required	
	score	4	4	3	4
Building codes requirements	Fire resistance [13]	Good	Excellent	Poor	
	Fire resistance	-4-260 C [13] melting at 1300 F (704 C) [30]	-240 – 800 C [13], melt at 2150 F (1177 C) [30]	(-)40 – 90C [13], doesn't burn readily, melt when expose to flame	Flammable, must be treat with fire retardant [4]
	Health Hazardous	Formaldehyde binders		Organic (Off-gassing, toxic smoke) [13], treat with fire retardant	nontoxic (the same low-toxicity and biodegradable flame retardant and insect/rodent repellent used in cellulose insulation and infant clothing)[28]
	Odor/skin irritation	Inorganic, Irritating dust during installation [13]	Inorganic, Irritating dust during installation [13]	non-irritating to work with	can install it without using respiratory or skin exposure protection
	score	3	3	4	3

Appendix

Scoring table of Loose fill Materials

	category	**traditional**			
	type	**Loose Fill**			
	materials	**Fiberglass (open cell structure)**	**Rockwool (open cell structure)**	**Cellulose**	**Perlite**
Thermal performance	min thermal conductivity	0.03	0.04	0.046	0.04
	max thermal conductivity	0.038		0.054	0.06
	average	0.034	0.04	0.05	0.05
	score	3	2	2	2
Cost	cost per R-value [13]	low	low	low	high
	price per sq. ft for 1 inch thick	-0.48		-0.85	
	score	4	4	4	1
Durability	[13]	compression and moisture degrade R-value	compression and moisture degrade R-value	compression and moisture degrade R-value	good
	score	3	3	3	4
Ease of construction	advantages	easy for the attic; well suited for places where it is difficult to install other types; generally fast to install	easy for the attic; well suited for places where it is difficult to install other types; generally fast to install	easy for the attic; well suited for places where it is difficult to install other types; generally fast to install	can be used and included in concrete
	disadvantages	settles after time if used in vertical applications; true R-value depends on quality of workmanship, amount of installation material; need special equipment and proffesional worker	settles after time if used in vertical applications; true R-value depends on quality of workmanship, amount of installation material; need special equipment and proffesional worker	true R-value depends on quality of workmanship, amount of installation material and moisture content; needs drying time if sprayed wet	limited use mostly between bricks
	score	3	3	3	2
Life-time Impact				0.25	
	score	4	4	4	4

Appendix

Recycle Impact					made out of rock - disposable
	score	3	3	3	4
Avialability					
	score	4	4	4	4
Building codes requirements	Fire resistance [13]	Very good	Execellent	Very good	Excellent
	Fire resistance				
	Health Hazardous			add fire resisting chemical	
	Odor/skin irritation			produces lower dust during installation	
	score	3	4	3	4

Appendix

Scoring table of State-of-the-art Materials

	category	state-of-the-art			
	type				
	materials	Aerogel	VIP	GFP	PCM
Thermal performance	min thermal conductivity	0.013	0.004	0.01	
	max thermal conductivity			0.046	
	average	0.013	0.004	0.028	#DIV/0!
	score	4	4	3	
Cost	cost per R-value [13]				
	price per sq. ft for 1 inch thick				
	score	1	1	1	1
Durability	[13]	offers constant design performance, no aging effects	loss of vacuum over time; easily damagable by daily activity	potential gas loss; easily damagable by daily activity	high because included in the wall material
	score	4	1	1	4
Ease of construction	advantages	wide range of building application; fast to install in new buildings: ease of maintanance			if embedded in the construction wall material (bricks, concrete, sheetrock) no extra insulation is needed); can be added to other insulation to improve their thermal performance
	disadvantages		need professional installation workers, not adjustable on construction site	need professional installation workers, not adjustable on construction site	no stand-alone insulation
	score	4	1	1	-
Life-time Impact		free of toxic ingredients		depends on used gas	
	score	4	4	2	

Appendix

Recycle Impact		free of toxic ingredients	no toxic materials in it	no toxic materials in it	embedded I other materials - hard to recycle; disposal?
	score	4	4	4	
Avialability					
	score	2	2	1	2
Building codes requirements	Fire resistence [13]				
	Fire resistence				
	Health Hazardous				
	Odor/skin irritation				
	score	3	4	2	1