Review of Different Components of Solar Decathlon House Projects

Ehsan Kamel[1], Ali M. Memari[2]

[1]Ph.D. Candidate, Department of Civil Engineering, Structural Engineering, Penn State University, 321 Sackett Building, University Park, PA 16802, E-Mail: mzk221@psu.edu
[2]Professor, Department of Architectural Engineering and Department of Civil and Environmental Engineering , Penn State University, 222 Sackett Building, University Park, PA 16802, E-Mail: memari@engr.psu.edu

Abstract

Reducing fossil fuel consumption and adopting solar energy can mitigate pollution problems and improve living conditions. The required energy to be consumed in a house could be provided by natural resources such as solar and wind energy. Solar houses are good examples of application of solar energy. Studying different components of these houses could lead to better understanding of the performance and application of different materials and methods in construction of even conventional houses, in particular energy efficient design.

In this paper, the past Solar Decathlon Competition projects are reviewed in order to categorize major load-bearing and non-load bearing components. In order to compare and assess the effect of each component, the following criteria as outlined by the solar decathlon competition rules are used: market appeal, affordability, comfort zone performance and energy balance. The components studied in this paper include floor, roof, wall systems, windows and glazing, insulation materials, and structural framing type. Another type of information that is gathered in the study includes available statistical analyses regarding the percentage of different structural framing and insulation types used in the design.

Keywords: Solar Decathlon competition, wall, roof, floor, window, glazing, insulation, structural frame, energy consumption, affordability

1. Introduction

A comfortable living space is one of the primary functions a house should provide. Cooling, heating, and ventilation that often rely on fossil fuel influence the comfort of the residents. Considering that buildings in this country consume one-third of the total energy and two-thirds of total electrical energy [1], it is essential to understand what features can be incorporated in the construction of homes to make them more energy efficient and sustainable. In particular, the use of renewable energy in production of electricity and "cleaner energy" would also benefit urban air quality [2].

Solar Decathlon Competition has been developed by the Department of Energy (DOE) to encourage such movement toward building sustainable houses. This competition was held in 2002 for the first time. Since then, it has occurred every two years in 2005, 2007, 2009, 2011 and 2013. The next competition will be held in 2015. The reports of these competitions have all been published, but the reports of the 2013 competition were not available in open literature at the time of this writing. The goal of this competition has been described to challenge student teams "to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive" [3]. The competition judges choose a team as the winner of the competition "that best blends affordability, consumer appeal, and design excellence with optimal energy production and maximum efficiency" [3].

Over the past few years, this competition has also taken place in Europe and China. The Europe competitions have been held in 2010 and 2012 and hosted by Spain, while and the next one will be held in 2014 in France. The China competition was held for the first time in 2013.

Designing and building solar-powered houses are among the multiple goals of this competition. For instance, on-site generation of energy is one of the most important goals of this competition. Other stated goals of the competition include "Educating students and the public about the money-saving opportunities and environmental benefits of using clean energy products and design solutions", "Demonstrating to the public the comfort and affordability of homes that combine energy-efficient construction and appliances with renewable energy systems available today", and "Providing participating students with unique training that prepares them to enter our nation's clean-energy workforce" [3]. The competition houses are first constructed in different locations, normally where schools are. Then they are disassembled, shipped to the competition place, which has always been at the National Mall in Washington D.C., and re-assembled there. The houses have been judged and ranked based on 10 different criteria. Table 1 presents the criteria considered in different years for this competition. Because the results of these contests are being assessed in Washington D.C., most of the teams design their houses for the climate of this location.

Table 1- Different Criteria in Solar Decathlon Competition [3, 13, 14, 15, 16]

2002	2005	2007	2009	2011
Design & Livability	Architecture	Architecture	Architecture	Architecture
Presentation & Simulation	Dwelling	Engineering	Market Viability	Market Appeal
Graphics & Communication	Documentation	Market Viability	Engineering	Engineering
Comfort Zone	Communications	Communications	Lighting Design	Communications
Refrigeration	Comfort Zone	Comfort Zone	Communications	Affordability
Hot Water	Appliances	Appliances	Comfort Zone	Comfort Zone
Energy Balance	Hot Water	Hot Water	Hot Water	Hot Water
Lighting	Lighting	Lighting	Appliances	Appliances
Home Business	Energy Balance	Energy Balance	Home Entertainment	Home Entertainment
Getting Around	Getting Around	Getting Around	Net Metering	Energy Balance

Multiple reports of houses designed by various teams who participated in these competitions contain valuable information about different types of solar houses. These houses generate their energy from solar radiation. The use of photovoltaic (PV) panels or solar water heaters can significantly reduce the electricity required, and if designed appropriately, the electricity supplied by photovoltaic panels can be used to operate the HVAC system too. Apart from solar systems, the structural parts can play an important role in reducing the energy consumption of the house as well. Components such as walls, floors, roofs, windows and insulations in different locations of the house can affect the energy consumption and market appeal of the house. To evaluate different assemblies, the following competition criteria are used: affordability, comfort zone, energy balance and market appeal. These criteria are discussed in section 3 in more details.

2. Components of the solar-powered houses

In order to decrease the energy consumption for heating and cooling of an occupied space in different climate regions, the efficiency and performance of different components of the house should be considered. In particular, walls, roofs, floors and windows are components that can affect the performance of a solar-powered house and are reviewed in this paper. Moreover, the insulation and structural frame types, that can affect the energy consumption and affordability of the house, are studied separately.

2.1 Walls:

Walls can be considered as one of the most crucial components of a sustainable house that can influence the energy consumption and related costs. Different studies have evaluated the performance of new wall systems in comparison with more conventional systems. These studies point out that a substantial amount of the energy used for space heating or cooling is lost through the walls [1,2 and 4].

Generally, the walls used by different teams throughout these years of the competition consist of an insulation core and different layers over the insulation and framing. Figures 1 through 3 illustrate the wall systems used by Darmstadt and Maryland teams in 2007, 2009 and 2011 [14, 15, 16]. These teams ranked first in these years.

The wall assembly of Darmstadt team (Figure 1) in 2007 consists of plexiglas for interior surface of the wall, phase change material (PCM) smart boards and rock wool as a sound insulation. PCM and prefab productions are not among the systems used by other teams in 2007. The wall assembly of Darmstadt team (Figure 2) in 2009 consists of plywood, gypsum board (GB), PCM smart boards and cellulose as a sound insulation. Hardly any other teams in 2009 used PCM, but plywood and gypsum board are common materials in different wall assemblies among other teams in 2009 competition. The wall assembly of Maryland team (Figure 3) in 2011 consists of wood-based products, gypsum board and spray foam as insulation. All of these materials were commonly used by other 2011 competition teams.

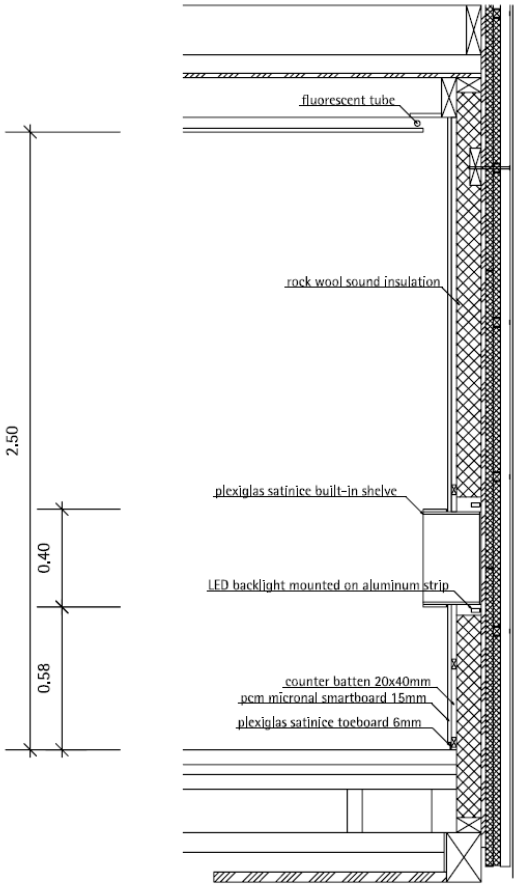


Figure 1- Typical wall section of Technische Universität Darmstadt team, ranked first in 2007 [14]

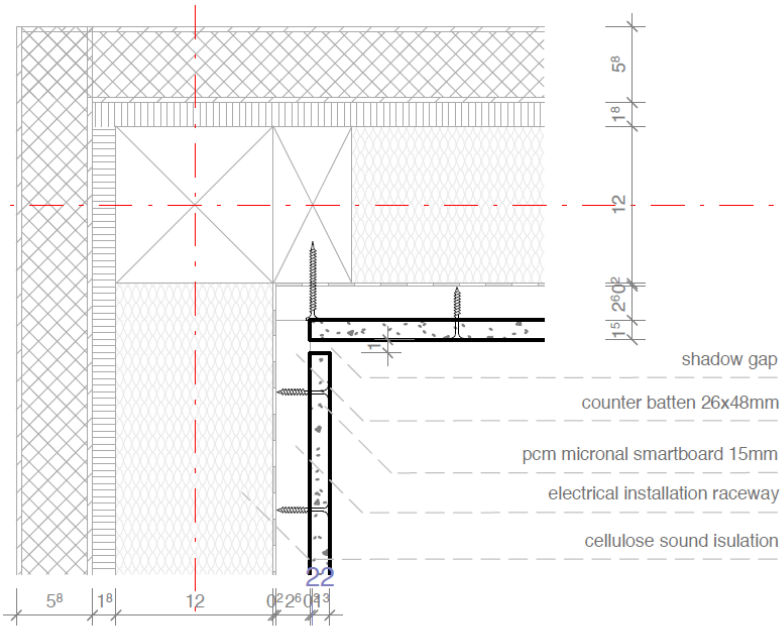


Figure 2- Typical wall section of Technische Universität Darmstadt team, ranked first in 2009 [15]

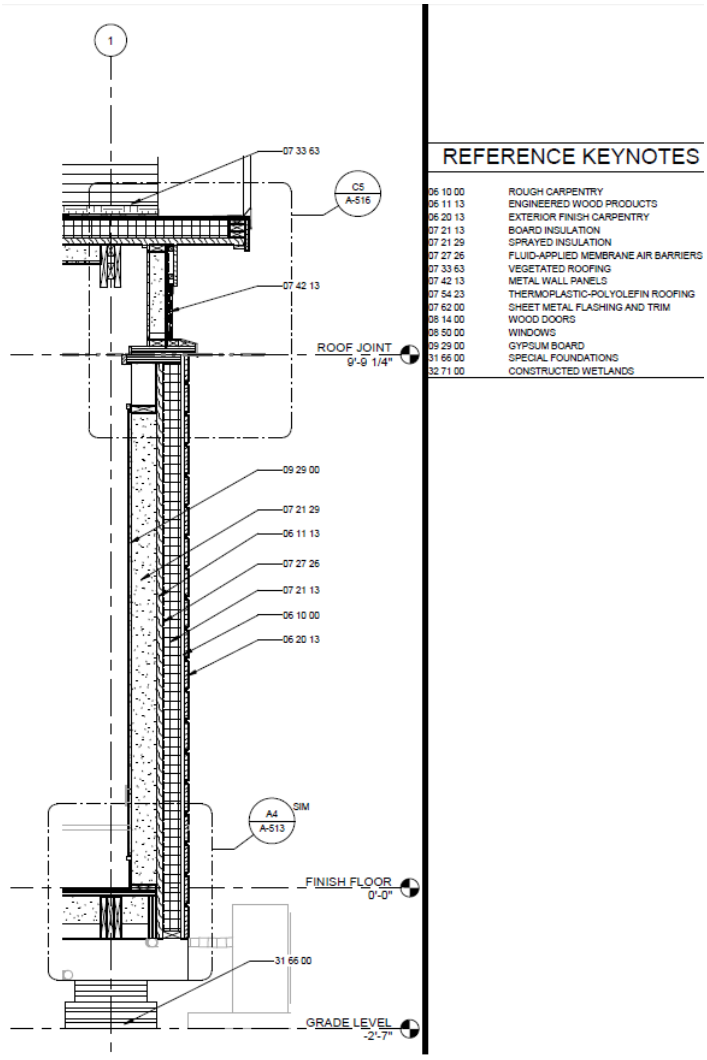


Figure 3- Typical wall section of team Maryland team, ranked first in 2011 [16]

Figures 4 and 5 illustrate different types of insulation and layers of these wall systems among different teams in 2007, 2009 and 2011 [14, 15, 16]. The wall insulation types are categorized into five different groups including: fiberglass batt, blown cellulose, spray foam, extruded polystyrene (XPS) and expanded polystyrene (EPS) as part of SIPs and Other types. Materials used as layers of the wall can be categorized into four groups including: plywood, other wood-based products (including oriented strand board (OSB) and timber board), GB and other materials (including concrete, metal board, fiber reinforced cement and prefab products).

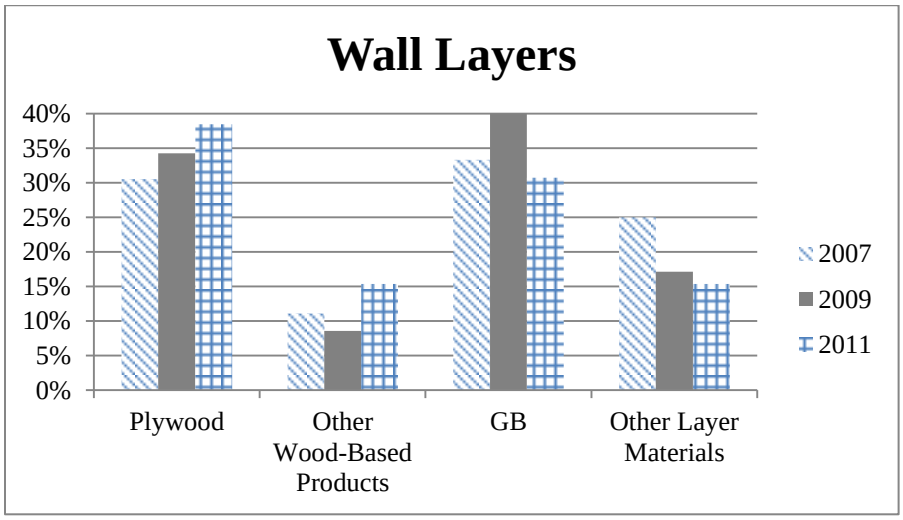


Figure 4 Percentage of different wall layer types used in Solar Decathlon competition

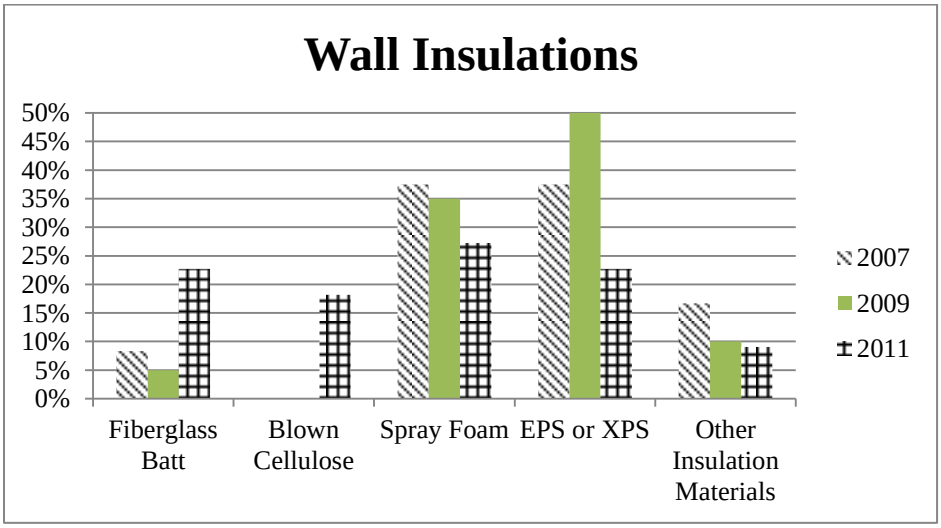


Figure 5 Percentage of different wall insulation types used in Solar Decathlon competition

As it can be observed, the plywood and GB are the most commonly used types of sheathing, respectively for exterior and interior application. Other types of wood-based products include OSB sheathing mainly used for exterior application. It is noted that the percentage of other types of wall materials used by some teams is higher than other wood-based products and that the increase in percentage of plywood has led to decrease in percentage of "other" insulation materials.

Regarding insulation types for wall assemblies, the EPS or XPS were mostly used in 2007 and 2009 as part of SIPs. The next highest used insulation material is spray foam. Other materials, including fiberglass batt, have been used the least in 2007 and 2009. Blown-in cellulose has not been used in these years. In 2011, spray foam was used slightly more than EPS products. Fiberglass and blown-in

cellulose are the next highest used types, followed by other products. Generally, it seems that spray foam and rigid foam (e.g., EPS) materials have been found to be more favored by most teams, and they are thought to have better performances for a climate like that of the Washington D.C.

2.2 Roofs:

Same as the wall systems, roof assemblies are of high importance and can influence the energy consumption of the house. Different types of roof assemblies used in previous competition usually consist of an insulation core and different layers over the insulation and framing. Figures 6 through 8 illustrate the roof systems used by the Darmstadt and Maryland teams in 2007, 2009 and 2011 [14, 15, 16]. These teams ranked first in these years.

The roof assembly of Darmstadt team (Figure 6) in 2007 consists of OSB, fiber cement board and vacuum insulation. Both fiber cement board and vacuum insulation were hardly used by other teams in 2007, but OSB seems to be more common among other teams who participated in the 2007 competition. The roof assembly of Darmstadt team (Figure 7) in 2009 consists of OSB as sheathing. Two different types of the insulation used in this assembly are vacuum insulation and EPS. Again, vacuum insulation was rarely used among other teams in 2009, but the wood-based products and EPS insulation material both are common materials among other teams. The roof assembly of Maryland team (Figure 8) in 2011 consists of two different types of the insulation in the assembly: board insulation and spray foam with gypsum sheathing. Both of these materials were used by other teams as well.

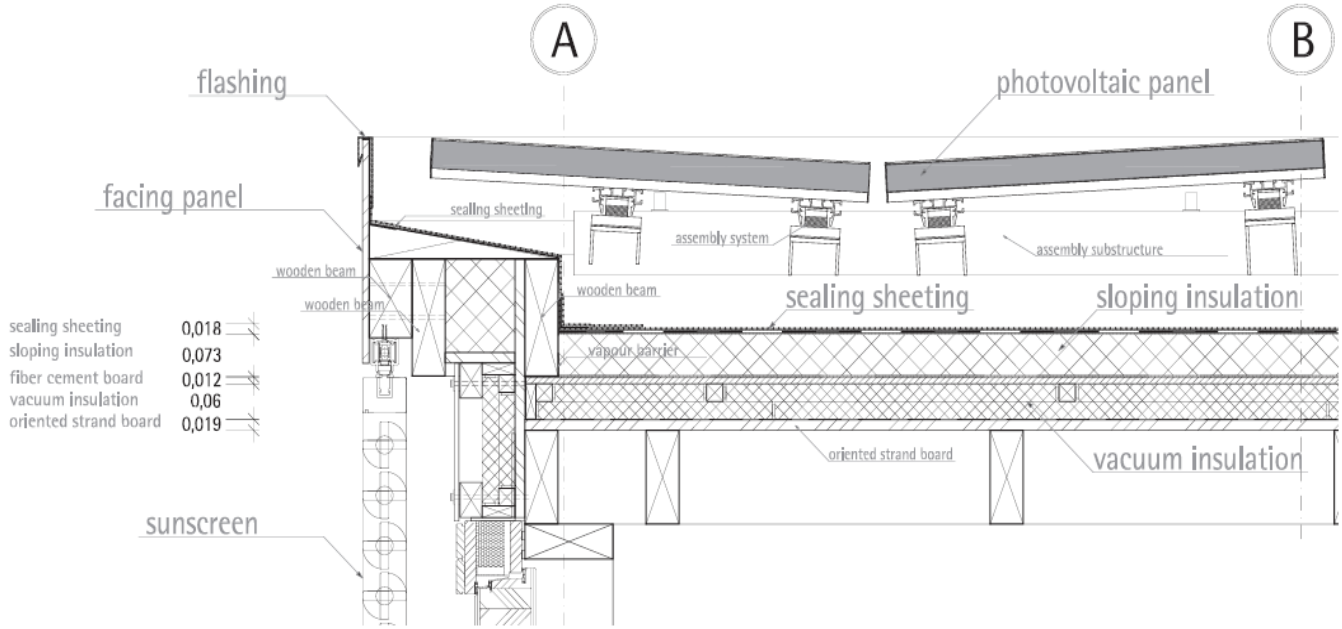


Figure 6- Typical roof section of Technische Universität Darmstadt team, ranked first in 2007 [14]

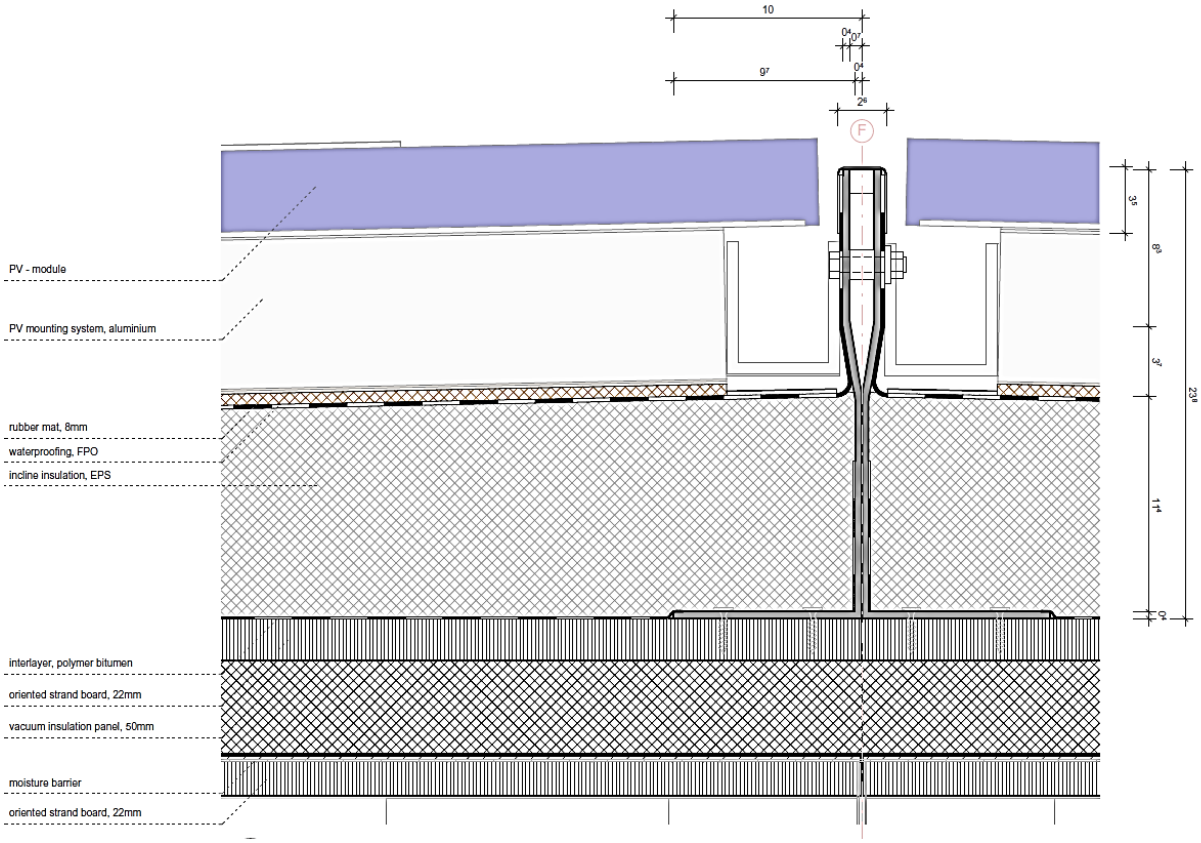


Figure 7- Typical roof section of Technische Universität Darmstadt team, ranked first in 2009 [15]

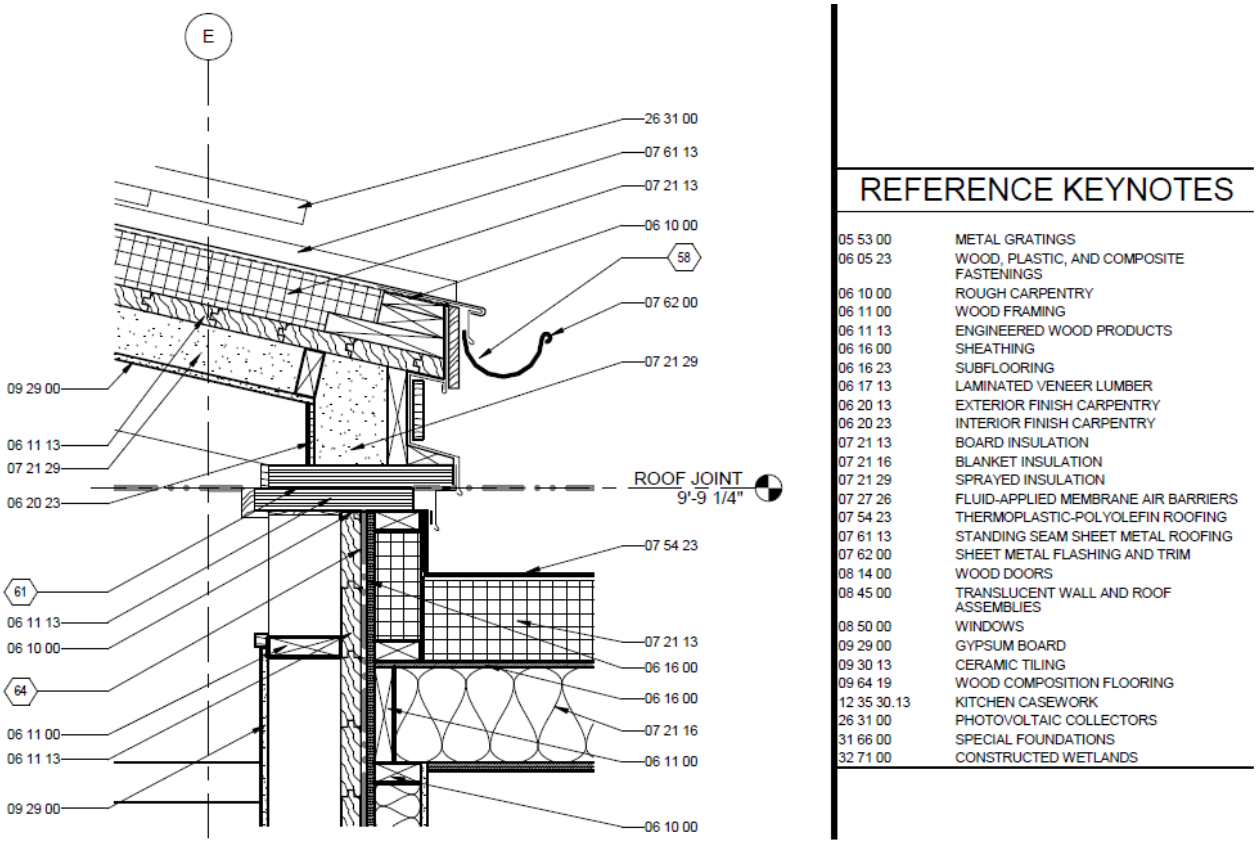


Figure 8- Typical roof section of team Maryland team, ranked first in 2011 [16]

Figures 9 and 10 illustrate different types of insulation and layers of these roof systems among different teams in 2007, 2009 and 2011 [14, 15, 16]. The roof insulation types are categorized into five different groups including: fiberglass batt, blown cellulose, spray foam and XPS or EPS as part of SIPs. Materials used as layers of the roof can be categorized into four groups including: plywood, OSB, GB and other materials (including Vegetated roof, PVC, thermo plastic materials, metal panel, aluminum deck, precast concrete and prefab productions).

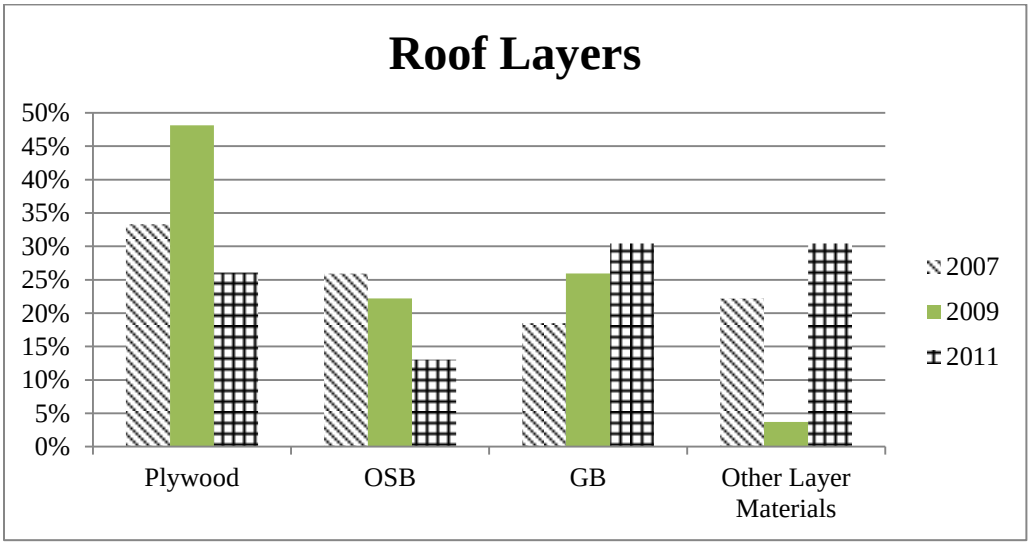


Figure 9- Percentage of different roof layer types used in Solar Decathlon competition

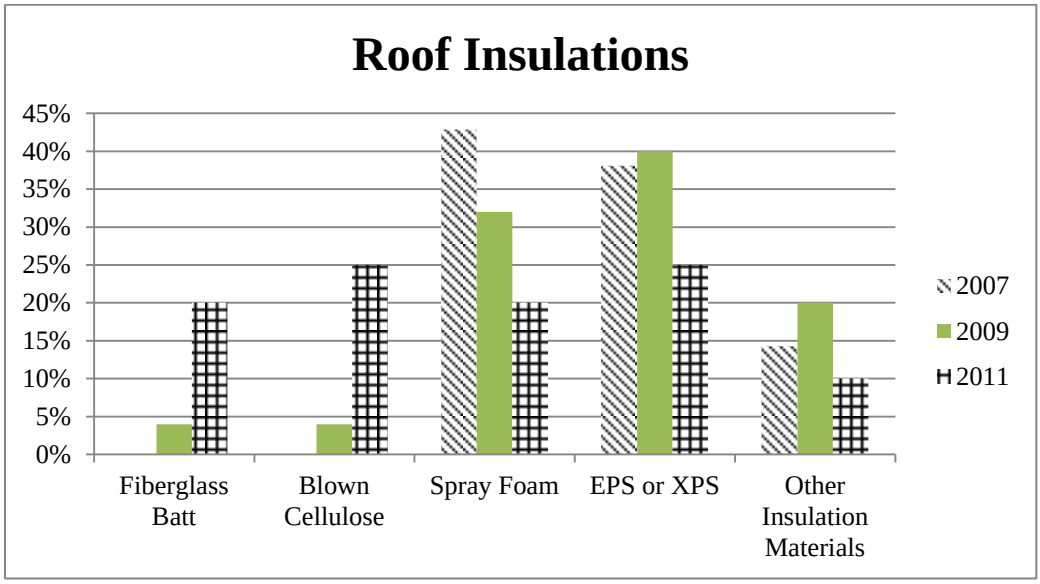


Figure 10- Different roof insulation types used in Solar Decathlon competition

Figure 4 shows that the percentage of GB has increased in these three years of the competition. In 2011, the competition teams preferred to use more innovative roof systems and it led to a decrease in percentage of plywood and an increase in other products in contrast with 2009.

Figure 10 shows that the use of spray foam and EPS products has decreased and the cheaper products like blown-in cellulose and fiberglass batt have been used more. In 2011, all insulation types are approximately used with the same percentages, while in 2007 and 2009; EPS products and spray foam are used more than other materials.

2.3 Floors:

Floor systems are mostly affected by ground temperature and moisture. Both of these factors can affect the durability and energy consumption of the house. In floor systems in contact with ground selecting proper system and materials are of high importance. The flow of heat to the ground from a building and the other way around depends on a complicated thermal process [7, 8]; therefore, learning from the experiences of such a competition can be helpful.

Beside the conventional floor systems used in buildings, in recent years, there has been a renewed interest in heated concrete slab floors to provide for space heating in both residential and commercial buildings [5]. Different types of floors used by competition teams consist of an insulation core and different layers over the insulation and framing. Figures 11 through 13 illustrate the floor systems used by the Darmstadt and Maryland team in 2007, 2009 and 2011 [14, 15, 16].

The floor assembly of Darmstadt team in 2007 (Figure 11) consists of wood-based products sheathing and sandwich panels as insulation. All the materials were commonly also used by other teams in 2007. The floor assembly of Darmstadt team in 2009 (Figure 12) consists of wood and gypsum board as sheathing and styrofoam as insulation. All the materials were also commonly used by other teams in 2009, except for Knauf boards and some insulation materials under the parquets. The floor assembly of Maryland team in 2011 (Figure 13) consists of wood-based products sheathing and spray foam as insulation. All of these materials were also used by other teams.

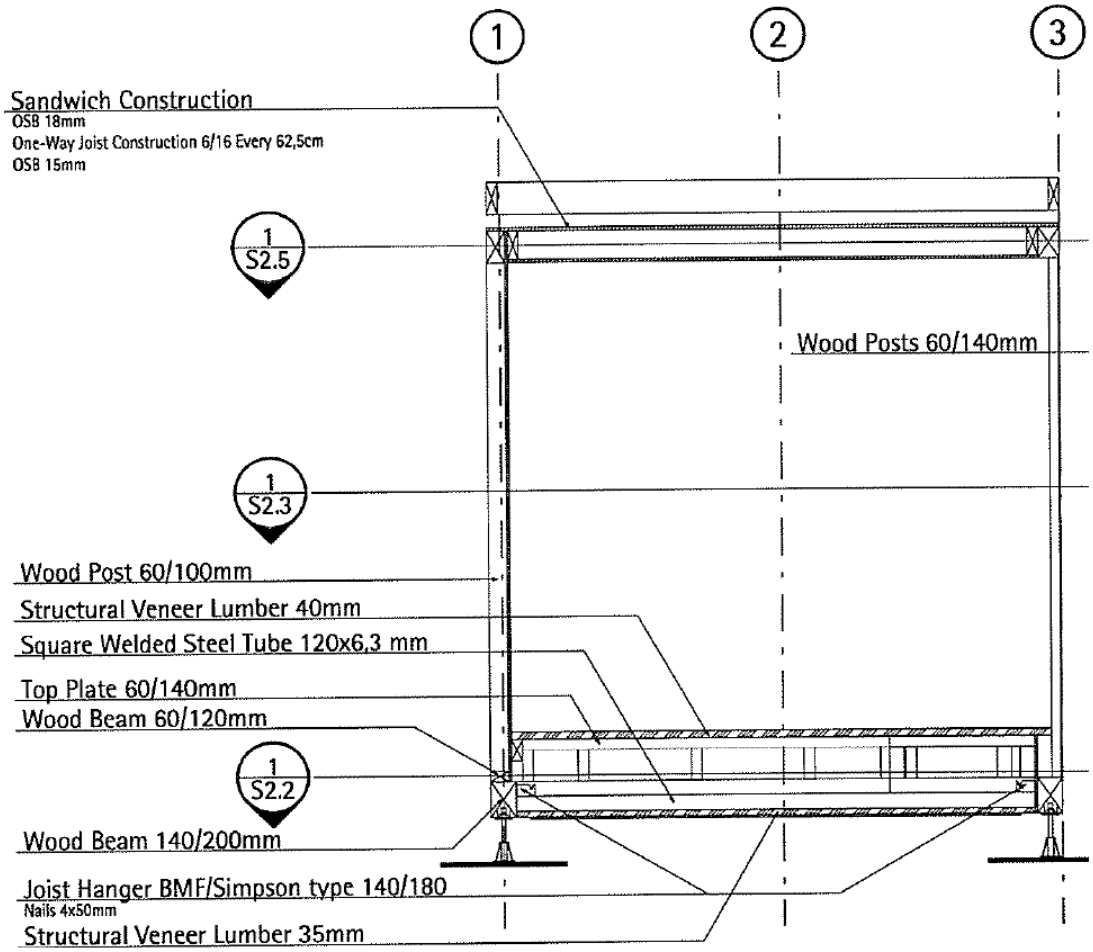


Figure 11- Typical floor section of the Technische Universität Darmstadt team, ranked first in 2007 [14]

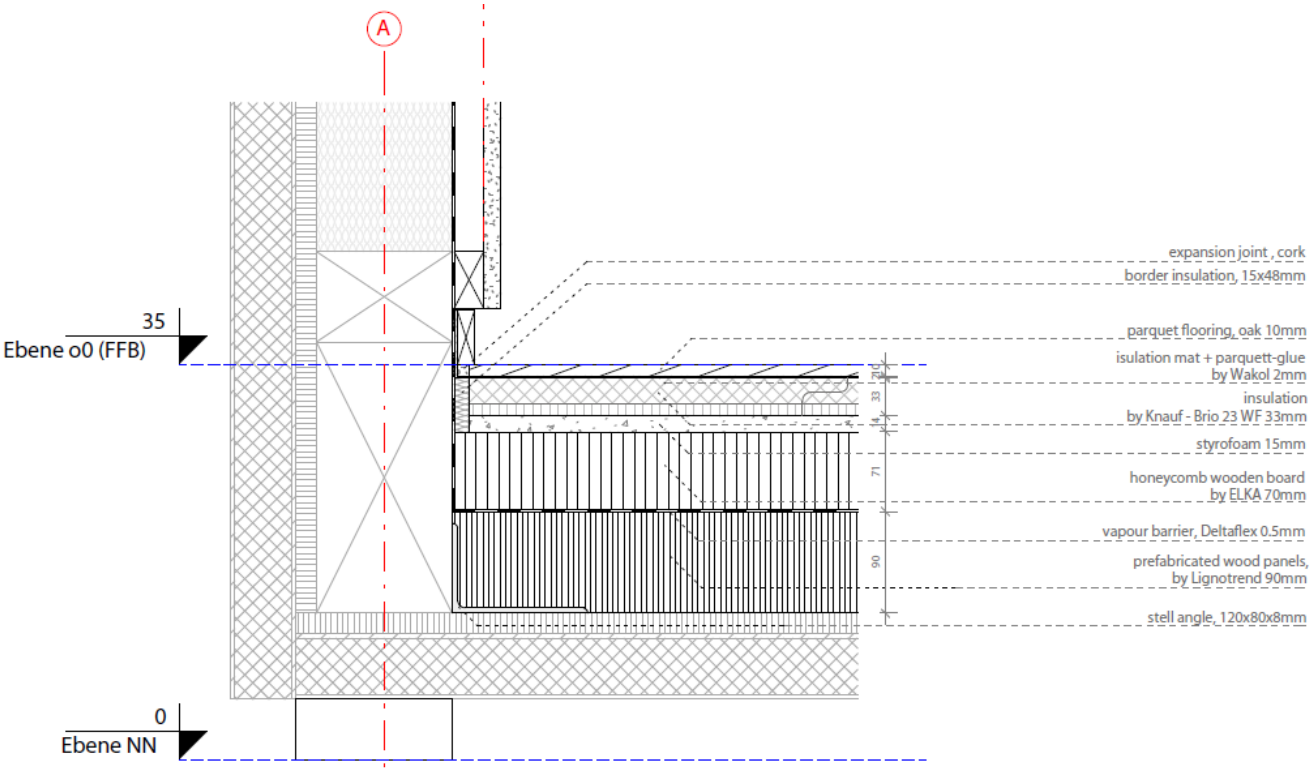


Figure 12- Typical floor section of the Technische Universität Darmstadt team, ranked first in 2009 [15]

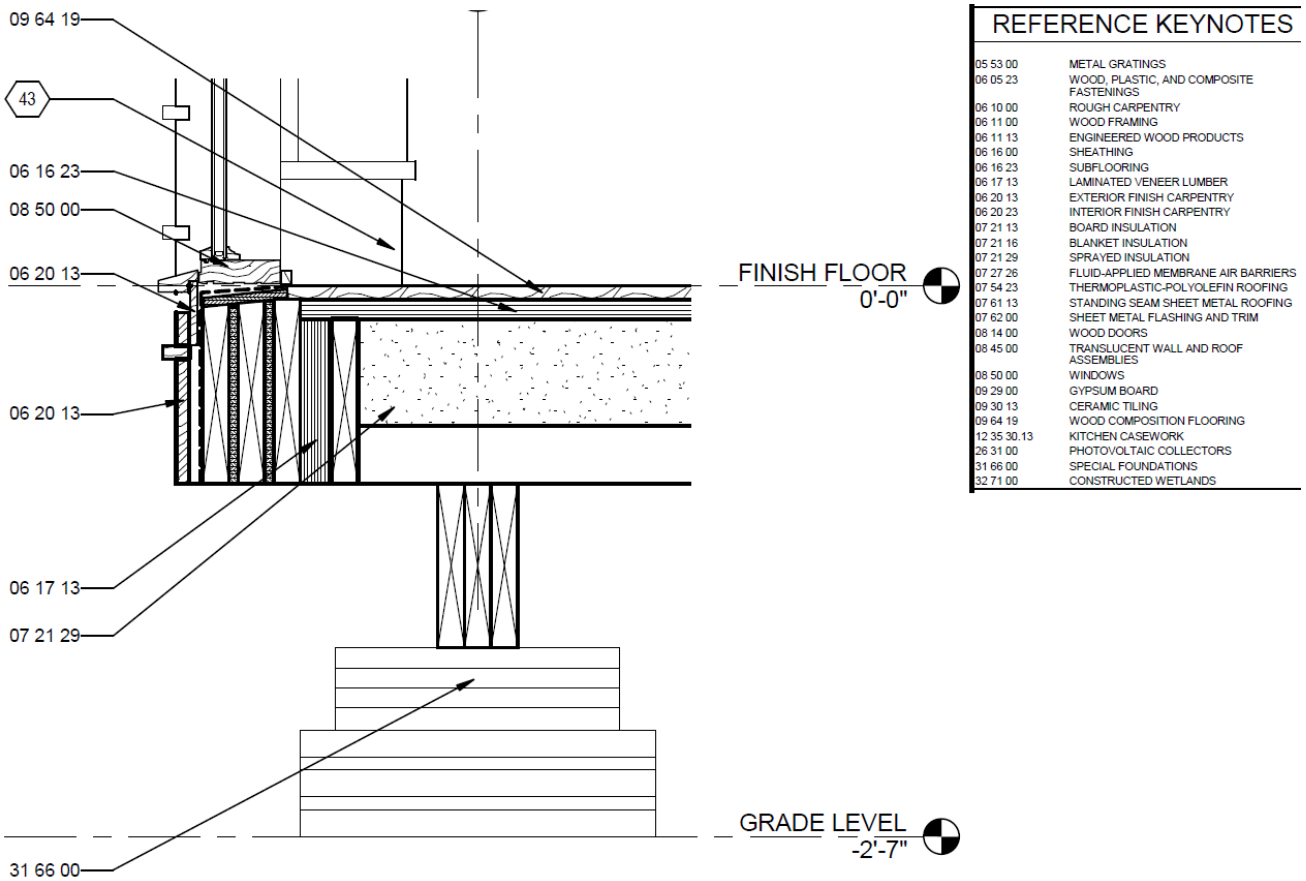


Figure 13- Typical floor section of the Maryland team, ranked first in 2011 [16]

Figures 14 and 15 illustrate different types of insulation and layers of floor systems used by different teams in 2007, 2009 and 2011 [14, 15, 16]. The floor insulation types are categorized into four different groups including: fiberglass batt, blown cellulose, spray foam and XPS or EPS as part of SIPs. Different materials used as layers of the floor can be categorized into three groups including: plywood, other wood-based products (including OSB) and timber board and wood strips) and other materials (including concrete and prefab products).

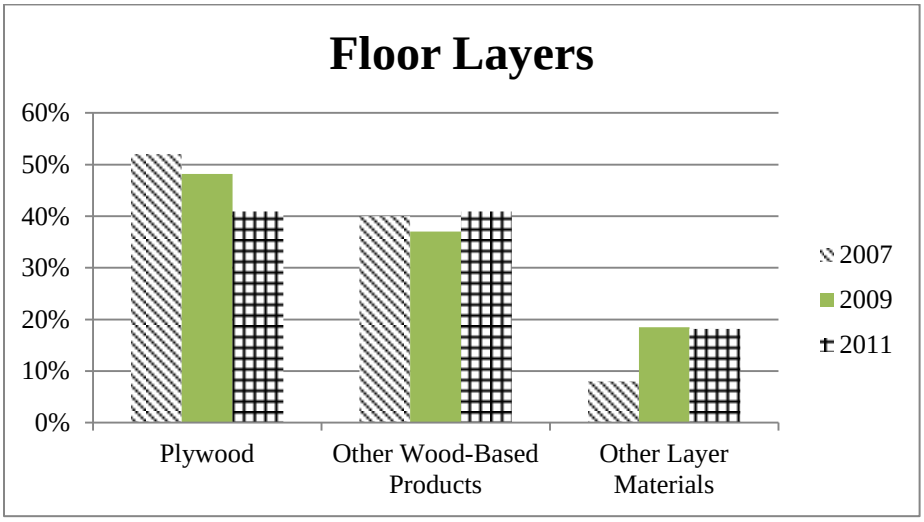


Figure 14- Percentage of different floor layer types used in Solar Decathlon competition

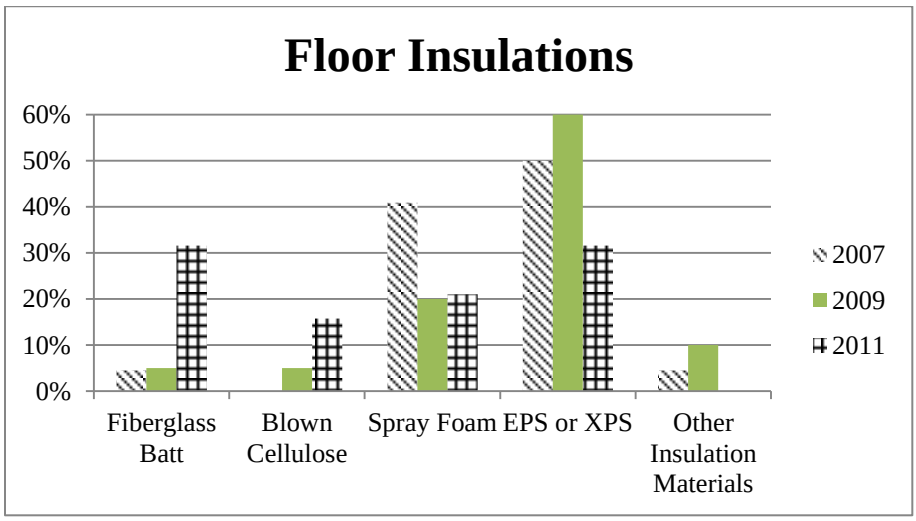


Figure 15- Different floor insulation types used in Solar Decathlon competition

There are no significant changes in the percentage of floor layer types in these three years of the competition. It can be noticed that the team's tendency toward using more innovative or prefab assemblies has increased slightly, and it has led to a decrease in plywood percentage.

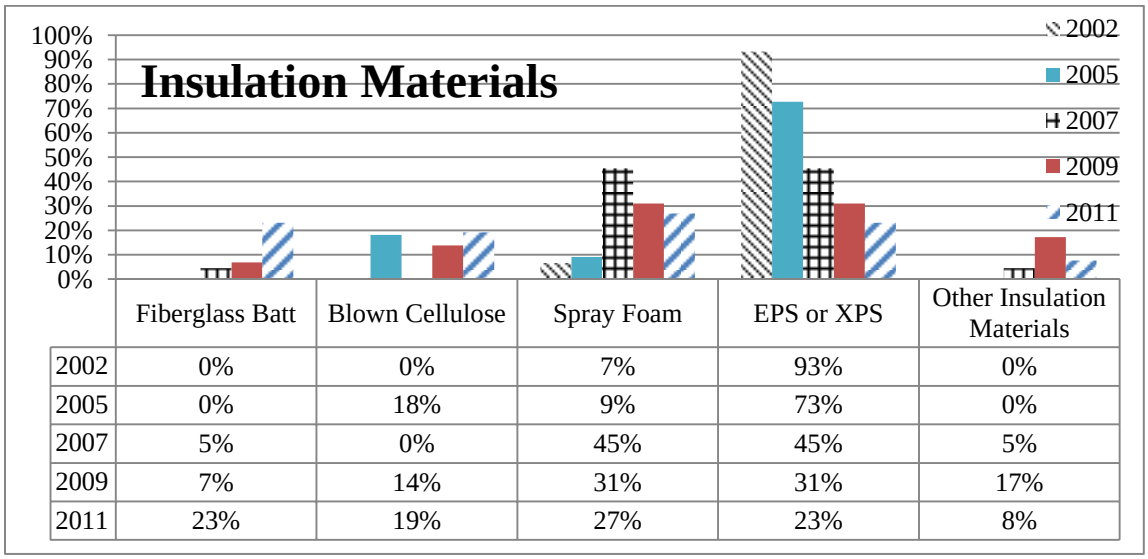
Regarding the floor insulation types, it can be observed that percentage of fiberglass and blown-in insulations has increased, and it has led to a decrease in spray foam and EPS products use. This increase could be due to both cost and energy effects of these insulations. Generally, the EPS products and spray foam are used more than other insulations.

2.4 Insulation materials:

The magnitude of energy savings as a result of using thermal insulation could vary according to the building type, the climatic, as well as the type of the insulating material used [8]. Numerous insulation materials are available in the market, including polyurethane, mineral wool, EPS, XPS and gas insulation panels. There are also new and innovative materials or technologies evolving; examples are vacuum insulation panels, nano insulation materials, aerogels and dynamic insulation materials. Currently, there exist no single insulation materials or solution capable of fulfilling all the requirements with respect to the most crucial properties [9].

There are not enough data available about the insulation types in 2005 reports of the competition. Moreover, in the 2002 competition, most teams used SIPs, which means the insulation material was likely EPS, XPS or polyurethane. Various types of insulations are used in 2007, 2009 and 2011. Figure16 demonstrates the percentage use of different types of insulation [3, 13, 14, 15, 16]. These insulations are used for both heat and sound insulation in wall, floor and roof sections. The insulations are categorized into five different groups including:

1) Fiberglass batt
2) Blown cellulose
3) Spray foam
4) EPS or XPS as part of SIPs
5) Others (including rigid sheets, innovative materials, denim fiber, rock wool and etc.)



	Fiberglass Batt	Blown Cellulose	Spray Foam	EPS or XPS	Other Insulation Materials
2002	0%	0%	7%	93%	0%
2005	0%	18%	9%	73%	0%
2007	5%	0%	45%	45%	5%
2009	7%	14%	31%	31%	17%
2011	23%	19%	27%	23%	8%

Figure 16- Percentage of different insulation material types used by the Solar Decathlon competition teams

2.5 Windows and glazing:

The characteristics of the building envelope can affect interior temperature and humidity among other parameters, which can then affect the occupant's comfort [10]. In particular, because windows have much less insulation than opaque parts of the envelope and are generally transparent, they can affect the mean radiant temperature and normally let solar radiation into the house.

The parameters that can vary and yield different window types include number of the glazing lites or panes, type of the in-fill gases (usually noble gases), and coatings. Furthermore, innovative window systems have been developed that can act like a thermal mass while allowing solar radiation to penetrate through, and also there are windows that incorporate photovoltaic. The studies on photovoltaic integrated windows indicate that solar windows can annually produce about 35% more electric energy per unit cell area compared to a vertical flat photovoltaic module [11, 12].

Teams in Solar Decathlon competition have used different window systems. The features of these glazing systems can be categorized into 7 groups including: tempered double pane, triple pane, low-e argon fill, air fill, krypton fill and insulated glasses. Figure 17 illustrates percentage of different types of features in windows used by different teams in each year [14, 15, 16].

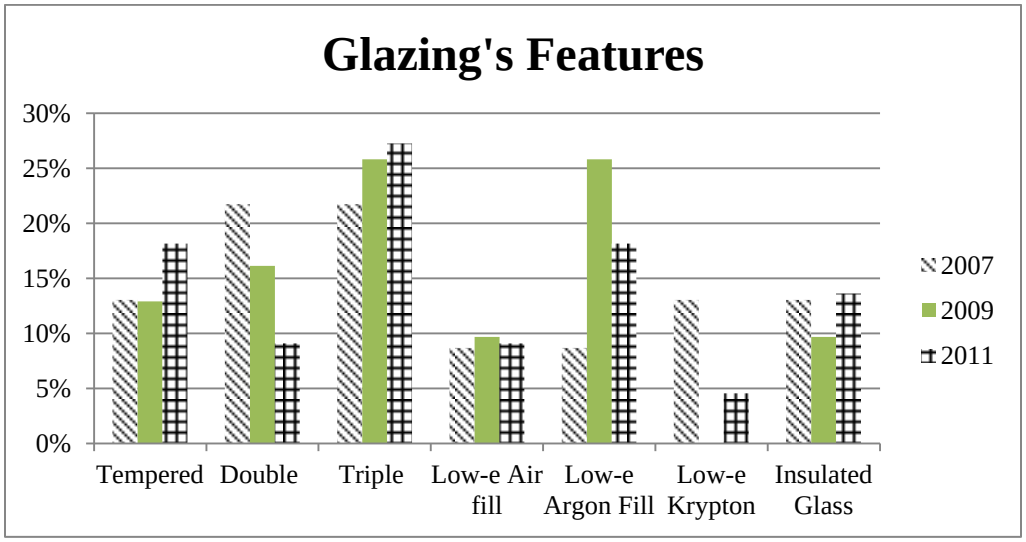


Figure 17- Percentage of different features of glazing used by different teams in 2007, 2009 and 201

Figure 17 shows that the use of percentage of using insulated glass and low-e air-filled glass did not changed significantly for the three competitions. While the use of low-e argon-filled, tempered and triple pane glasses increased. On the other hand the use of low-e krypton-filled and double pane glass decreased.

It seems that the increase in use of triple pane and low-e glass filled with argon could be due to their better performance in cold climate of the Washington D.C. Moreover, tempered glass filled with air has been another option due to its lower cost.

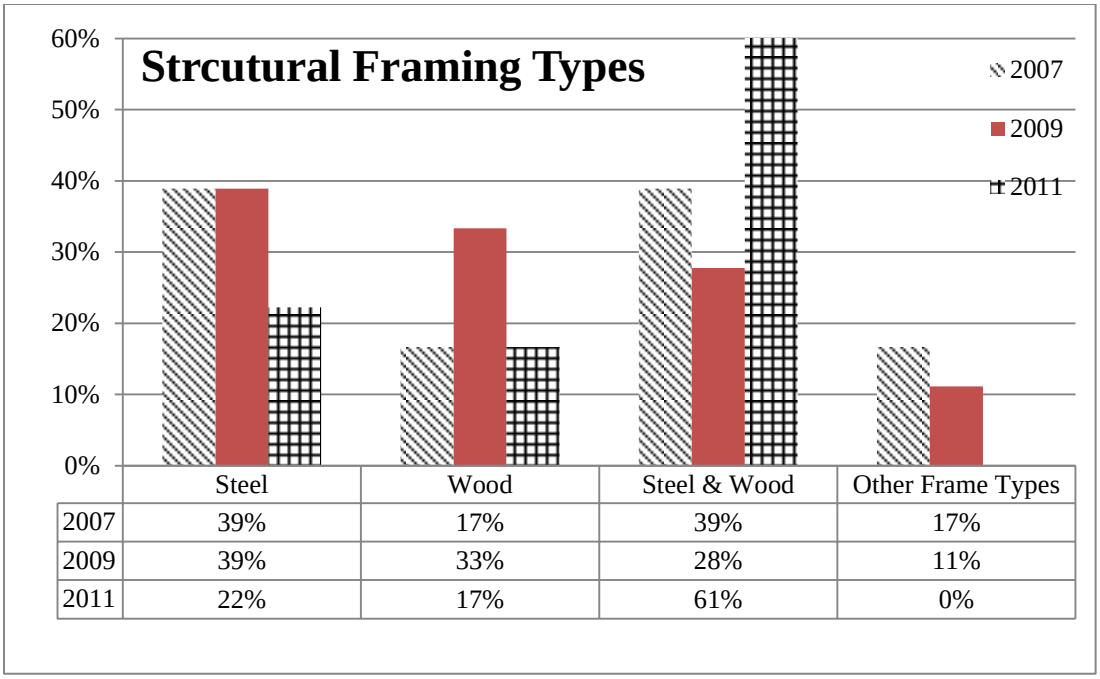
2.6 Structural framing:

Structural framing of the house can affect the properties of the house mainly in three ways. First, it can affect the choice of thermal insulation for the envelope. Second, it can affect directly the initial cost of the house. Finally, the durability properties of the envelope can be influenced directly by the materials and other characteristics of the structural frame.

In 2002 and 2005 competitions, almost all teams used Structural Insulation Panel (SIP) systems, while in 2007, 2008 and 2009 other framing systems have been used. These framing systems could be categorized into four groups including:

1) Whole steel members (including rolled and built-up sections)
2) Whole wood members
3) Combination of wood and steel members
4) Others (including aluminum and composite members)

Figure 18 illustrates the percentage of each structural framing system types used in different years of the competition [14, 15, 16].



	Steel	Wood	Steel & Wood	Other Frame Types
2007	39%	17%	39%	17%
2009	39%	33%	28%	11%
2011	22%	17%	61%	0%

Figure 18- Percentage of different structural framing system types used in Solar Decathlon competition

Generally, the tendency toward using combination of wood and steel in structural frames has increased. But, in most of these frames, the studs are made of wood and some other components made of steel. Wood and composite (wood & steel) structures altogether are found to be more favored types of frames by different teams.

3. Criteria

3.1 Affordability:

This criterion was included to the contests of the competition in 2011 for the first time. The affordability criterion encouraged teams to design and build affordable houses that combined energy-efficient construction and appliances with renewable energy systems. This way, the teams demonstrated how energy-saving features can help consumers save money right away. Professional estimators determined the construction cost of the houses. Teams earned 100 points for achieving a target construction cost of $250,000 or less. A sliding point scale was then applied to houses with estimated construction costs between $250,001 and $600,000. Houses with estimated costs more than $600,000 would receive zero points [3].

Although there are different components and appliances in these houses affecting the final price of the house, it might be useful to see how different wall, roof, floor, window and structural framing systems can affect the affordability of the house, regardless of other components, equipment and appliances.

3.2 Comfort zone:

For the 2011 competition Comfort Zone criterion, teams designed their houses to keep temperature and humidity steady, uniform, and comfortable. Full points were awarded for maintaining narrow temperature and relative humidity ranges during specified periods of time [3].

For full points, the houses had to maintain the following:

- Temperatures between $71^{\circ F}$ ($22.2^{\circ C}$) and $76^{\circ F}$ ($24.4^{\circ C}$).
- Relative humidity less than 60%.

3.3 Energy Balance:

For the Solar Decathlon 2011 competition, each team equipped their house with a bidirectional utility meter that enabled competition organizers to measure the net energy a house produced or consumed over the course of the competition. In the Energy Balance Contest, a team received full points for producing at least as much energy as its house needed, thus achieving a net energy consumption of zero during the contest week. This was accomplished by balancing production and consumption [3].

3.4 Market appeal:

Teams built their houses for a target market of their choosing. They were then asked to demonstrate the potential of their houses to keep costs affordable within that market. A jury of professionals from the homebuilding industry evaluated how well-suited the houses were for everyday living, determined whether the construction documents would enable a contractor to construct the houses as intended, and assessed whether the houses offered potential homebuyers within the target market a good value. The jury considered the following criteria [3]:

- Livability-Whether the house is well suited for everyday living, could accommodate the specific needs of the targeted homeowners, and offers a safe, functional, convenient, comfortable and enjoyable place to live.
- Buildability-Whether the construction documents would enable a contractor to generate an accurate construction cost estimate and then construct the building as the design team intended it to be built.
- Marketability-The house's curb appeal, interior appeal, and quality craftsmanship; how well its sustainability features and strategies contribute to its marketability; and whether the house offers potential homebuyers within the target market a good value.

4. Review of solar decathlon competition reports

4.1 General data

The format of reports in different years is not the same. Therefore, there is lack of information about some details of house components like window and glazing in reports of 2002 and 2005 competition. As a result, the data from each year is demonstrated separately in Tables 3 through 6.

As it was discussed earlier in section 3, the following four criteria have been used to evaluate the effect of different components on energy balance and affordability: affordability, comfort zone, energy balance and market appeal. These criteria have not been used in every competition. Table 2 demonstrates the year in which each of these criteria has been used. Due to lack of information in the reports of 2002 and 2005 competitions, the data from these years are not reflected in this paper.

Table 2- Use of different criteria in each year of competition [3]

Year	Affordability	Comfort Zone	Energy Balance	Market Appeal
2007		✔	✔	✔
2009		✔		✔
2011	✔	✔	✔	✔

Effects of different components on energy balance and affordability

Table 3 demonstrates top 3 teams in 2007, 2009 and 2011 based on the comfort zone criterion and lists different components use by the teams.

Table 3- Different components of top three teams in 2007, 2009 and 2011 based on comfort zone criterion [14, 15, 16]

Teams	Comfort Zone Ranking	Glass Type	Frame Type	Wall Type	Insulation Type	Roof	Floor
Illinois (2007)	1	insulated glazing	wood	GB-OSB-spray foam	spray foam	OSB-spray foam	bamboo-OSB-spray foam
NYIT (2007)	2	Low-e krypton fill	steel & wood	plywood-GB-spray foam	spray foam	SIP-plywood	SIP-plywood
Texas (2007)	3	double pane low-e	steel	GB-plywood-SIP	EPS	plywood-SIP	warmboard-plywood-SIP
Germany (2009)	1	triple pane	steel & wood	plywood-PCM-GB	vacuum insulation panel	Wood-OSB vacuum panel	OSB-Knauf-styrofoam
Illinois (2009)	2	triple pane	wood	Plywood-GB-Wood-based products	foam in-place	bamboo foam in-place	plywood-bamboo-steel tray-foam in-place
Ontario/BC (2009)	3	-	steel & wood	plywood closed cell polyurethane spray foam-veneer plywood	closed cell polyurethane spray-Mineral wool insulation	EPDM roofing membrane plywood closed cell polyurethane spray	plywood closed cell polyurethane spray-plywood
Ohio State (2011)	1	low-e, tempered triple glazed krypton fill	steel & wood	batt-GB loose fill insulation	fiberglass batt and loose-fill	OSB-GB-batt fibrous cement	batt insulation composite deck plywood
Purdue (2011)	2	-	laminate lumber-plywood	plywood-spray&batt foam-PTFE coated glass polyester	spray&batt foam	plywood-spray&batt	plywood
Maryland (2011)	1	low e argon fill	steel & wood	GB, sprayed foam wood	sprayed foam	thermoplastic polyolefin-sprayed & board foam	sprayed foam board insulation wood-based products

The top three teams in 2007 used insulated glazing, low-e filled with krypton gas and double pane low-e glass to address the comfort zone criterion. In particular, the teams identified triple pane glass and low-e glass filled with a noble gas as most efficient for their application. Most of these teams used spray foam for insulation of opaque walls. Fiber glass batt, EPS and foam-in-place are other types of insulations used.

Almost all wall assemblies used GB and plywood. Other types of wood-based products and SIPs were used too. Moreover, almost all of the roof systems were composed of plywood or other wood-based products. The same is true for the floor systems.

Table 4 demonstrates top teams in 2007 and 2011 based on the energy balance criterion and lists different components used by the teams.

Table 4- Different components of top teams in 2007 and 2011 based on energy balance criterion [14, 15, 16]

Teams	Energy Balance Ranking	Glass Type	Frame Type	Wall Type	Insulation Type	Roof	Floor
Carnegie Mellon (2007)	1	tempered-argon filled	steel	metal panel wood	metal panels	wood-GB-aluminum	wood-GB-aluminum
Cincinnati (2007)	1	krypton filled	steel & wood	plywood spray foam	spray foam	spray foam plywood mdf	spray foam plywood rubber flooring
Darmstadt (2007)	1	three glass panes	steel & wood	PCM smart board, plexiglas batten	rock wool polyurethane foam vacuum insulation	fibrous composite-OSB-vacuum insulation	plywood sandwich panel
Maryland (2007)	1	low-e tempered	steel aluminum	GB, plywood, spray foam	spray foam	spray foam rigid insulation	plywood warm board
Montréal (2007)	1	double and triple pane	steel aluminum	wood soy urethane	soy urethane	wood cladding soy urethane steel deck	wood cladding soy urethane steel deck
Santa Clara (2007)	1	smart window	wood	plywood batt&spray foam	cotton batt-polyurethane spray	plywood polyurethane spray acrylic coating	poly urethane spray
Florida International (2011)	1	-	steel & wood	plywood-metal board-spray foam- batt	sprayed foam-batt	plywood-spray foam -stretched fabric	wood floor-sprayed foam plywood
Illinois (2011)	1	tempered	steel & wood	plywood-rigid foam board GB foam in-place	foam board -foam in place	GB-foam board	prefab panel plywood foam in-place
Maryland (2011)	1	low e argon fill	steel & wood	GB sprayed foam wood	sprayed insulation	thermoplastic polyolefin-sprayed & board foam	sprayed foam board insulation wood-based products
New Zealand (2011)	1	double & triple glazed-air fill	wood steel concrete	plywood-wool batt insulation-timber board	wool batt insulation	plywood-wool batt insulation-timber board	concrete-plywood wool batt wood panel
Purdue (2011)	1	-	wood	plywood-spray & batt foam - PTFE coated glass polyester	spray foam -batt foam insulation-	plywood-spray foam -batt foam insulation-	plywood-wood floor decking
Tennessee (2011)	1	single, triple & quadruple pane-tempered-glazing	steel & wood	plywood-rigid foam-GB foam in-place	batt insulation	plywood-batt insulation-EPDM roofing-rigid	batt-plywood rigid insulation

Six teams ranked first in 2007 and 2011 based on the energy balance criterion. Most of these teams used triple pane, low-e filled with argon or krypton windows. Moreover, spray foam is the most used insulation type among these teams. In wall, roof and floor assemblies, plywood and other wood-based products are mostly used in these teams.

Table 5 demonstrates top 3 teams in 2007, 2009 and 2011 based on the market appeal criterion and lists different components used by teams.

Table 5- Different components of top three teams in 2007, 2009 and 2011 based on market appeal criterion [14, 15, 16]

Teams	Market Appeal Ranking	Glass Type	Frame Type	Wall Type	Insulation Type	Roof	Floor
Illinois (2007)	1	-	wood	GB-OSB sheathing-	honeywell polyurethane foam	reflective acrylic coating - spray foam-OSB	bamboo flooring-spray foam -OSB sheathing
Maryland (2007)	2	low e - tempered	aluminum wood	GB - corrugated metal-cypress-plywood	spray foam	spray foam insulation-rigid-polycarbonate skylight	plywood-cypress decking
Puerto Rico (2007)	3	double insulated - tempered	structural fiberglass column&wood	GB - GRC panel	SIP, rigid insulation	treated plywood sheet	SIP-plywood-radiant heating board-ash wood
Univ. of Louisiana (2009)	1	-	steel	SIP-GB-perforated aluminum - plywood	soy based spray foam	SIP	SIP
Rice (2009)	2	-	aluminum wood	corrugated metal-cdx plywood	icynene (open-cell spray)	plywood sheathing-icynene -gypsum board	plywood sheathing-icynene - gypsum board
Team California (2009)	3	-	steel & wood	plywood-thermablock-demilec spray insulation-plywood	soy based spray	plywood-bamboo - demilec spray insulation-ecorock plate	warmboard-glass mineral wool-cotton wood-soy based
Middlebury College (2011)	1	argon-filled safety glass	steel & wood	GB and wallboard-plywood-cellulose	cellulose insulation	cellulose-metal panel--zip system panel	-
Maryland (2011)	2	low e argon fill	steel & wood	GB-sprayed-wood-based products-air barrier	sprayed foam	thermoplastic polyolefin roofing-sprayed	sprayed foam-wood-based products
New Zealand (2011)	3	triple glazed-air filled, double	wood-steel-concrete	plywood-wool batt -timber board	wool batt	plywood-wool batt - timber board	concrete-plywood-wool batt -cedar

For market appeal criterion, most of top teams in 2007, 2009 and used wood in their structural framing accompanied by other materials like steel or aluminum. The same as the other houses in previous rankings, the spray foam insulation is the most used one. EPS products, cellulose and wool batt are other types used. GB and plywood are mostly used in wall assemblies in these houses. In roof systems, the plywood is mostly used as sheathing but there are some other materials like reflective acrylic coatings or thermoplastic polyolefin roofs as well. In floor assemblies, plywood is the mostly used type and in one case, concrete slab is used as well.

Table 6 demonstrates top three teams in 2011 based on the affordability criterion and lists different components used by the teams.

Table 6- Different components of top teams in 2011 based on affordability criterion [16]

Teams	Affordability Ranking	Glass Type	Frame Type	Wall	Insulation Type	Floor	Roof
Team Belgium (2011)	1	-	steel	mineral fiber cement- SIP	foam board	wood foam board	plywood foam board
Parsons NS Stevens (2011)	1	tempered –high performance-low e, argon blend filled insulating glass	wood	OSB-GB blown-in	blown-in cellulose- polyisocyanurate insulation board	-	polyvinyl chloride roofing-high density polyisocyanurate board-OSB blown-in insulation
Purdue (2011)	2	-	wood	plywood spray foam-batt	spray foam and batt	wood-plywood spray foam-batt	plywood spray foam-batt

Affordability is mainly related to the cost of the materials and systems used in the envelope. The top three teams in 2011 mostly used wood framings with the exception that the first team used steel framing. Insulation types are diverse. Spray foam, batt, blown-in cellulose and foam board are among the insulations used by these teams. In wall assemblies, again there are variety of materials like OSB, GB, fiber reinforced cement board and plywood. Wood materials are used in floor and roof systems in these top teams based on affordability criterion.

5. Summary and conclusions

In this paper, different components of the houses designed for the Solar Decathlon Competition were reviewed including insulation, structural framing, window types, and wall, roof and floor assemblies. The effect of these components on affordability, energy consumption and living comfort was assessed based on the criteria used in this competition. Four major criteria considered in this paper are affordability, comfort zone, energy balance and market appeal. Generally, based on the provided information it can be observed that:

1) Gypsum board (GB) and plywood are the most commonly used types of sheathing for wall, roof and floor.
2) Sheathing in different assemblies is not diverse enough to be able to judge their effects on each criterion, and most of the teams used approximately the same types of sheathing. Therefore, it is appropriate to also study the properties of other systems such as mechanical and electrical systems.
3) According to the considered criteria, the spray foam has been identified to have the best performance. But, based on affordability criterion, the houses that have used other types of insulation like fiberglass batt, foam board and blown-in cellulose are higher ranked because spray foam is more expensive than other insulation materials.
4) In comparison with 2002 and 2005 designs where EPS products were often used, spray foam percentage use increased significantly in more recent competitions.
5) In 2007 and 2009, the EPS products and spray foam are mostly used in wall, floor and roof assemblies. In 2011, the EPS productions and spray foam percentage use has decreased and other types of insulation like fiberglass batt and blown-in cellulose are used more than before. This might be because of team's tendency toward decreasing the costs.

6) Triple pane, tempered, low-e argon filled and insulated glasses are used by most teams. It seems that these features lead to better performance for window systems compared with double pane glass in climate zone of Washington D.C.
7) Generally, wooden structural framings have been shown to be more favored by the teams. However, the combination of wood and steel framings is also highly favored. Other framing types like concrete and aluminum are least favored.

6. References

1. Aldawia, F., Alama, F, Date, A., Alghamdib, M., and Aldhawi, F., (2013). "A new house wall system for residential buildings", Energy and Buildings, 67, 403–418
2. Aldawi, F., Date, A., Alam, F., Khan, I., and Alghamdi, M., (2013). "Energy efficient residential house wall system", Applied Thermal Engineering, 58, 400-410
3. U.S. Department of Energy, Solar Decathlon official website: www.solardecathlon.gov; (Dec. 02, 2013)
4. Aldawia, F., Alam, F., Date, A., Kumara A., and Rasul, M., (2012). "Thermal performance modelling of residential house wall systems", Procedia Engineering, 49, 161 – 168
5. Delsantet, A., and Landman, K., (1987). "Steady-state heat losses from a building floor slab with vertical edge insulation II", Building and Environment, 22, 1, 49-55.
6. Claesson, J., and Hagentoft, C., (1991). "Heat loss to the ground from a building i. general theory", Building and Environment, 26, 2, 195-208 0360-1323.
7. Chuangchid, P., and Krarti, M., (2001). "Foundation heat loss from heated concrete slab-on-grade floors", Building and Environment, 36, 637–655.
8. Davidsson, H., Perers, B., and Karlsson, B., (2010). "Performance characteristics and practical applications of common building thermal insulation materials", Solar Energy, 84, 365–372.
9. Petter, B., (2011). "Traditional, state-of-the-art and future thermal building insulation materials and solutions – properties, requirements and possibilities", Energy and Buildings 43, 2549–2563
10. Cappellett, F., Prada, A., Romagnoni, P., and Gasparella, A., (2014). "Passive performance of glazed components in heating and cooling of an open-space office under controlled indoor thermal comfort", Building and Environment 72, 131-144.
11. Shaviv, E., (1984). "The performance of a passive solar house with window sunspace systems", Energy and Buildings, 7, 315 – 334.
12. Davidsson, H., Perers, B., and Karlsson, B., "Performance of a multifunctional PV/T hybrid solar window", Solar Energy, 84, 365–372.
13. U.S. Department of Energy, Solar Decathlon official website, Solar Decathlon (2005). "The Event in Review", October 7–16
14. U.S. Department of Energy, Solar Decathlon official website, Solar Decathlon (2007). Team as-built drawings: Carnegie Mellon, Cincinnati, Colorado, Cornell, Darmstadt, Georgia, Illinois, Kansas, Lawrence, Madrid, Maryland, MIT, Montréal, NYIT, Penn State, Puerto Rico, Rolla, Santa Clara, Texas, Texas A&M
15. U.S. Department of Energy, Solar Decathlon official website, Solar Decathlon (2009). Team as-built drawings: Arizona, Cornell, Illinois, Iowa State, Kentucky, Minnesota, Ohio State, Penn State, Puerto Rico, Rice, Alberta, Boston, California, Germany, Missouri, Ontario/BC, Spain, Univ. of Louisiana, Virginia Tech, WI-Milwaukee
16. U.S. Department of Energy, Solar Decathlon official website, Solar Decathlon (2011). Team as-built drawings: Appalachian State, Canada, Florida Int'l, Hawaii, Illinois, Maryland Middlebury College, New Zealand, Ohio State, Parsons NS Stevens, Purdue, Belgium, China, Florida, Massachusetts, New Jersey, New York, Tennessee, Tidewater Virginia