A TRANSPORTABLE AND ENERGY OPTIMIZED RESIDENTIAL BUILDING ARCHITECTURAL DESIGN FOR THE MONGOLIAN CLIMATE

A dissertation presented

by

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to

Breuer Marcel Doctoral School of Architecture,

Univer sity of Pecs, Faculty of Engineering and Information Technology

for the degree of

Doctor of Philosophy in the subject of

Architecture engineering

Pecs, Hungary

201

APPROVAL SHEET

This dissertation proposal entitled A TRANSPORTABLE AND ENERGY OPTIMIZED RESIDENTIAL BUILDING ARCHITECTURAL DESIGN FOR THE MONGOLIAN CLIMATE submitted by TSOVOODAVAA GANTUMUR for degree DOCTOR OF PHILOSOPHY has been examined and approved for PROPOSAL HEARING.

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Doctor of Philosophy in Architecture Engineering

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Abstract

The intensity of human activities adversely affects nature, and the environmental surroundings and climate change. As part of the initiatives reducing the adverse impacts, sustainable architecture importance is increasing. Depending on the climate, culture, and lifestyle, the residential buildings in the world have varying architecture. One of the unique architecture is nomadic architecture. For the nations with nomadic culture, transportable housing type is dominantly used. However, in the field of transportable building, there is a lack of research on building physics. This type of residential building challenges more the architectural and engineering design in respect of material and structure selection attached to mandatory characteristics of portability, indoor comfort, the feasibility of energy generation and operation in various sites, and energy efficiency.

The research aims to improve existing yurt in terms of indoor comfort and energy efficiency without sacrificing the key concepts of the yurt and that is compatible with the Mongolian climate. Mongolian context has selected as the base environment as it has one of the most extreme and severe climates in the world. To fulfil the set of objective, as inception the literary review on the various transportable residential building has performed which has found there are

9 different shapes of yurts used around the globe. On the basis of the 9 types of yurts found, the best shape yurt is identified through the comparative analysis using dynamic thermal simulation method.

The development has conducted within the frame of yurt opening, orientation, structural material, building system. For each of the component, various versions are tested and optimized using simulation tool IDA-ICE 4.8 and the best outcomes are determined in terms of energy efficiency and indoor comfort. Finally, the best versions are combined to form the optimized transportable residential building.

The study contributes to the development of nomadic vernacular buildings in terms of indoor comfort and energy efficiency which is notably novel in the building physics research of the nomadic vernacular architecture.

Keywords: transportable residential building, vernacular architecture, nomadic culture, energy optimization, indoor comfort, Mongolian climate, yurt, ger.

Pécsi Tudományegyetem
Műszaki és Informatikai Kar
Breuer Marcell
Doktori Iskola

ACKNOWLEDGMENTS

I would like to thank for the Tempus Foundation for granting me a Stipendium Hungaricum Scholarship which opened and supported my path to studying at the Architectural Engineering PhD program at the University of Pecs. I would like to express my sincerest thanks to Marcel Breuer Doctoral School of the University of Pecs for providing high standard PhD level education. This journey would not have succeeded without the support from two supervisors Prof. Dr. Habil. Kistelegdi Istvan and Associate Prof. Dr. Halada Miklos.

Special thanks to Dr. Kistelegdi Isvtan's enormous and generous directions through these exciting academic years and for letting me join in his 'Energia Design' research group. The warm, friendly, active atmosphere among the research group colleagues have made my research days more interesting and proactive.

Also, my gratitude goes to my colleagues and professors at Mongolian University of Science and Technology.

I would like to express my deepest thanks to my mom Khishgee Seded for her support and love for all the time. My deepest and greatest appreciation goes for my lovely wife Ninjin Bolortsogoo's powerful motivations and sharing all the feelings that she has been experiencing the same PhD journey while she has been caring the entire family with deep love. Also, I thank for my son Tushig and daughter Nandin for charging my energy with their beautiful being.

Tsovoodavaa Gantumur

ACRONYMS

CFD	Computational fluid dynamics
AHU	Air handling units
PPM	Past per million
PPMV	Past per million by volume
WHO	World health organization
OR	Orientation
OP	Opening
SM	Structure and material
SY	System
OM	Operation management
PCM	Phase Change Material
VIP	Vacuum Insulation Panel
PPD	Predicted Percentage of Dissatisfied
PMV	Predicted Mean Vote
HVAC	Heating Ventilation and Air Condition
BC	Before Century
IDA-ICE software	IDA- Indoor Climate and Energy dynamic thermal building simulation
N	North
S	South
W	West
E	East
NE	North East
NW	North West
SE	South East
SW	South West
IAQ	Indoor Air Quality

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1. INTRODUCTION

1.1. Background of research

The intensity of human activities adversely affects nature, and the environmental surroundings followed by climate changes apart from the many signs of progress and developments invented by humans. The footprints of human living related to lack of sound management include a reduction in pure water resource, air pollution, solid waste and which are countless to mention which have especially intensified during the past 50 years. The adverse environmental and social footprints are necessitated to be reduced through people's daily actions which involve architecture and development in architectural science.

In the architectural sector, the initiatives are set to contribute to environmental protection. One of them is Architecture 2030, that they set a big target to make entire new buildings to be Net Zero Energy by 2030 (Kjell, 2014) (Di Giuseppe, n.d.). In the settled building architecture and construction, there is a growing number of progressing works held by famous architects and engineers in the green building sector (Voss, 2012) (Thomas, 2012). However, there is a lack of researches in the transportable building sector. The transportable building is an essential means of housing in nomadic culture countries. In addition, it is important for the people who are involved in seasonal and occasional delegations in lack of infrastructure, and for a certain extent useful for tourism purposes.

One of the oldest, classic and widely dispersed types of transportable building is the 'yurt', which is common and fundamental for nomads (Banzragch, 2006). The main features of the yurt are portability, ergonomic and environmentally friendly properties which fit for the purpose of dealing with environmental problems as well as human shelter needs. The yurt's structure, materials, and operations have not been changed significantly since ancient times (Banzragch, 2006) (Bat-Ulzii.B, 2016). However, in this modern society, people's requirements on living standard, comfort, and social needs are incomparably changed and increased from those back to thousands of years. In addition, there is a lack of prior study on indoor comfort and energy consumption on yurts.

1.2. Research objective

The main objective of this research is to study indoor comfort and energy consumption of current yurts, which are vernacular, traditional and transportable residential buildings and to develop a modern yurt, which improves the indoor comfort and energy consumption.

1.3. Overview of Mongolia

The main research context is focused on Mongolia. The energy efficiency and indoor comfort are much dependent on the climate, natural and cultural factors. Therefore in this section, the history and current status of the country, and climate, geographical and natural conditions are introduced.

Mongolia is a landlocked country located between China and Russia at the heart of Central Northern Asia. It has 1,564,116 km^2 territory that makes the country 18th biggest country in the world. Mongolia consists of 21 provinces (aimag), 329 sub-provinces (soum) and the capital city is Ulaanbaatar. As noted in Manalsuren, the last and truly nomadic country in the world is Mongolia (Manalsuren, 2017). The population is 3,057,778 (Urandchimeg.B, 2017) of which 87.4 thousand live abroad and 49.2 % of the population is male and 50.8% is female (Urandchimeg.B, 2017) (Report, 2015) 68% of the population lives in urban and 32% live in rural areas in Mongolia (*Figure 1*) (Report, 2015).

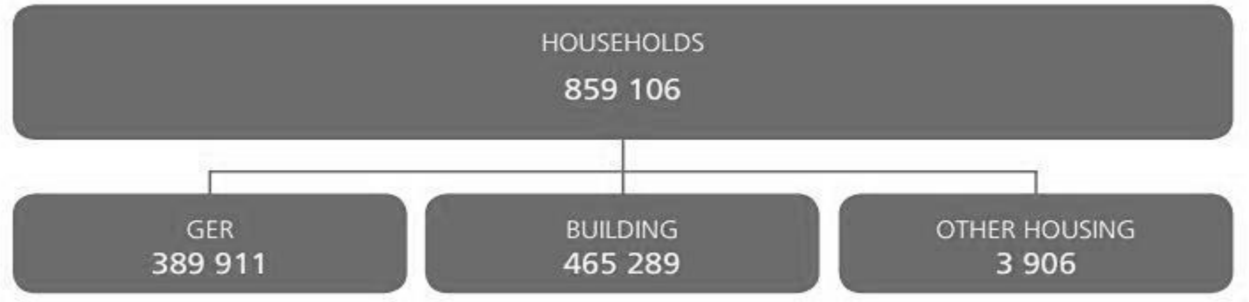


Figure 1: Households housing types of Mongolia (Report, 2015).

1.4. Overview of climate, geographical zones of Mongolia

1.4.1. Natural condition

Mongolia is located between 41° 35’ and 52° 06’ of north latitude, and in between 87° 47’ and 119° 57’ of east longitude. The land boundaries are 8082 kilometers and the distance is 1259 kilometers from north to south, 2392 kilometers west to east (Angerer, 2014). It is surrounded by high mountains and exists at 1580 m altitude and the highest point is Nairamdal peak, Tavan Bogd Mountain which is elevated 4374 m above the sea. The lowest point is Khukh nuur (Blue Lake) with 552 m altitude (Punsalmaa, 2005) (Angerer, 2014) (Dagvadorj, 2009).

<u>Natural zones</u>: There are 6 different geographical zones in Mongolia (Ministry of Nature, 2011) which are illustrated in below *Figure 2*.

<u>Alpine or high mountain zone</u>: The high mountain zone covers only 5 percent of Mongolian entire territory and which consists of Altai, Khangai, Khentii and Khuvsgul Mountains (Punsalmaa, 2005) (Angerer, 2014). In these areas, extremely cold climate dominates where the warm season does not stay long. The land features include highland swamp, meadows, tundra, and lichen-coated boulder (Punsalmaa, 2005).

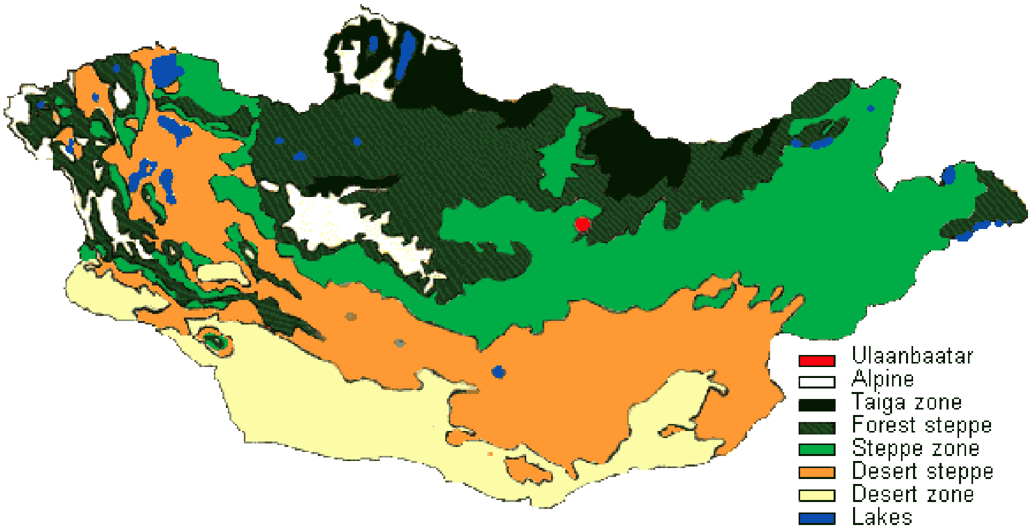


Figure 2: Natural geographical zones in Mongolia

Taiga or forest zone: The forest zone is presented in Northern Mongolia which also reflects only 5 percent of Mongolian territory. The associated lands cover: Khentii Mountains, Khuvsgul Lake terrain, the side part of Tarvagatai Mountain, River Orkhon terrain, and partially covers Khan Khukhii Mountain. It is one of the lowest temperature areas and steppe features have lightly induced (Schlütz, 2008).

Forest-steppe zone: 25 percent of the territory is covered by a forest-steppe zone which is a heavily populated area of Mongolia. The features related to mountain and steppe interchangeably exists in these areas. The areas include branches of Khentii, Khangai mountains terrain, Altai Mountain terrain, basins of Orkhon and Selenge, as well as in Khyangan Mountains (Dulamsuren, 2005).

Steppe zone: Steppe zone is dominated eastern territory of Mongolia, which is spread over the Khangai, Khan Khukhii Mountains to Depression of Great Lakes. Various group of plants and wild animals exist in the zone. The steppe referred to central and western sides of the country is highly affected by human footprints, including infrastructure, agriculture, and construction (Fernández-Giménez, 1999).

Desert steppe zone: Desert steppe zone locates in between steppe and desert zones that cover 20 percent of Mongolian territory which has a severe climate condition. Low level of annual precipitation of 100-124 mm, sensible to droughts, heavy winds, and strong dust storms is general in the area. Besides the climate condition, many Mongolian herders live in the area (Kurapova, 2012).

Desert zone: Significant territory of southern Mongolia is filled with the desert zone. It has widely dispersed vegetation, various settings land soils. The desert zone is scarce in rain and snowfall as which shows lower than 100mm per annum. The wind speed reaches 140 km per hour and the dust storm is dangerous during spring and fall (Kurapova, 2012).

1.4.2. *Climate conditions in Mongolia*

Between the latitudes of 40º north and 60 º north, cool temperature climate zone is found in the northern hemisphere (Hausladen, 2012).

Air temperature: Mongolian climate has a very high-temperature variance between summer and winter in relation to its continental location (Hausladen, 2012). Air temperature in Mongolian ranges between 10ºC and 26.7 ºC in summer and -15 ºC and -30 ºC in winter (Punsalmaa, 2005) (Angerer, 2014) (Dagvadorj, 2009). The mean temperature in the mountain area is lower than -4 ºC. Between mountains and big rivers, the temperature is lower than -6 ºC to -8 ºC. In the steppes and desert zones, it is lower than 2ºC, while in the south Gobi desert, the average temperature is higher than 6 ºC (Dagvadorj, 2009).

The average temperature in the coldest month of January ranges in between -15 ºC and -34 ºC depending on the climate zone. However, the exceptions arise that the coldest temperature was recorded in December 1940 which reached -55.3 ºC in western provinces. In the capital city, the coldest temperature was recorded as -49.0 ºC in December 1954 (Angerer, 2014) (Dagvadorj, 2009).

Precipitation: Rain and snowfall level in Mongolia is low that the average precipitation shows 300-400 mm in the mountain zone, 250-300 mm in the forest-steppe zone, 150-250 mm in steppe and 50-100 mm in desert zones (Banzragch, 2006). In the winter season, the snowfall level ranges between 10 mm to 30 mm depending on the climate zone (Angerer, 2014) (Dagvadorj, 2009).

Sunshine: Mongolia is a relatively sunny place where it has 230-260 days of sunshine per annum. And on an hourly calculation, it takes 2600 to 3300 hours of sunshine per year (Dagvadorj, 2009).

Winds: Mongolia locates in comparatively windy terrain, in its steppe and desert steppe zones. The average speed of wind ranges between 2 and 6 m/s depending on the zone. In the desert zone (which is 41.3 percent of entire Mongolian territory) yearly dust storm occurrence hours range between 300 and 600 hours of which 61 percent happens in March. And which makes one of the main contributors to ‘Asian yellow dust’.

Climate Zones

In below, *Figure 3* illustrates four zones as numbered by I, II, III and IV. Zone I refers to the coldest temperature and others are numbered according to its temperature in ascending direction.

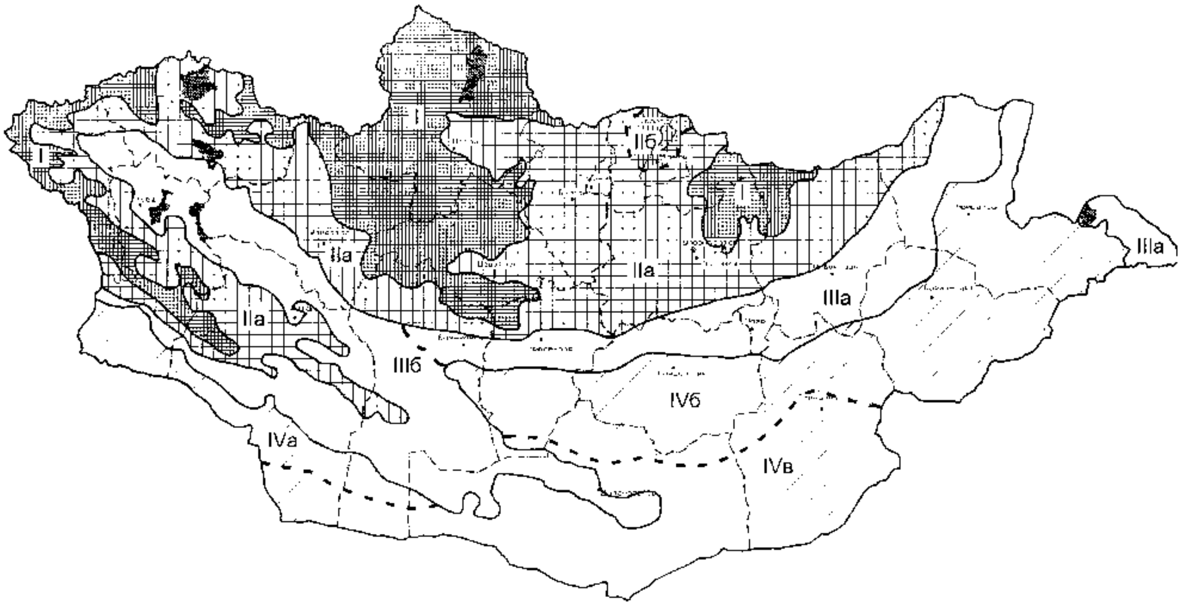


Figure 3:Climate zones for urban planning (Mongolia, 2004)

In *Table 1* climate and the geographic information is systemized on cases of chosen climate stations from all climate zones and subzones.

Table 3:Climate zones based on 'Meteonorm' climate database (Remund, 2016) (Sovacool, 2011).

Climate Zone	Name	Coordinate	Elevation	Minimum air temperature, °C	Maximum air temperature, °C	Relative humidity of air, %	Direct normal radiation, W/m2	Wind speed, x-component, m/s	Wind speed, y-component, m/s
I.	Tosontsengel	48,7N 98,3W	2108	-36	33	62.3	203.1	-0.3	0.1
II.a.	Ulyastya	47,7N 96,8W	1753	-36	33	60.0	211.6	0.0	-0.1
II.b	Sukhbaatar	50.2N 106.2W	1124	-35	34	70.1	194.2	-0.2	0.0
III.a	Choir	46.4N 108.4W	1269	-31	36	57.6	183.4	-0.5	0.1
III.b	Altai	46.4N 96.3W	2213	-35	28	67.4	213.8	-0.5	0.1
IV.a	Bulgan, Khovd	46,1N 91.5W	1189	-34	33	44.5	264.0	-0.2	0.3
IV.b	Choibalsan	48.1N 114.5W	747	-32	35	56.1	185.9	-0.5	0.2
IV.c	Sainshand	44.9N 110.1W	961	-28	39	51.8	269.7	-0.6	0.2
City	Ulaanbaatar	47.9N 106.7W	1350	-35	33	60.4	180.1	-0.0	-0.0

1.4.3. Renewable energy

The transportable building's energy source has to renewable and portable as the building should be able to locate in various condition places. Wind and solar radiation renewable sources are suitable for the transportable building. Other sources are hard to be transported and make the assembly complicated or impossible.

Mongolia is one of the countries which is included in the North-East Asian super grid for 100% renewable energy supply Mongolia is rich in renewable energy sources of solar radiation energy and wind energy, especially Mongolian Gobi desert is counted have a large renewable energy source in Asia (Komoto, 2013) (Bogdanov Dmitrii, 2016).

Nomadic people have been using renewable energy in a traditional way for thousands of years, which is the biomass from livestock animals for heating in the vernacular nomadic house. And the produced energy is sufficient for cooking. However, nowadays householders use coals and other materials for heating in the cities as it requires less process and space.

Wind energy

Up to 70% of the Mongolian area has wind resource, which is categorized into good to excellent wind resource of over 2550 terawatt-hour per year (Secretariat, 2013). The best resources are the Gobi desert and east two provinces which are located in the steppe where the wind capacity is estimated to reach 150-200W/m^2 for 4000-4500 hours per year.

The map is designed by National Renewable Energy Laboratory, Mongolia and US Department of Energy in 2000. The cooperation has studied wind energy of Mongolia. The findings show 40% of the total area of the country has the wind condition of good to moderate category, with wind speed between 5.6 to 6.4 m/s. More than 10% of the total country's area has good to excellent wind potential for utility-scale applications, with wind speed between 6.4-7.1m/s (Secretariat, 2013) (Tserenpurev Bat-Oyun, 2012).

Solar energy

The solar energy source can be used to electricity by the solar photovoltaic (PV) system and to generate heating solar thermal system (Francis DK Ching, 2014). It is assumed that a photovoltaic system's yield is about 180KW/m^{2}a in the ideal installation condition (Hausladen, 2012).

In Mongolia, approximately 71% of the total land area receives solar insolation at a rate 5.5-6 kWh/m^2 per day during the year, and 2900-3000 hours of sunshine per year (Komoto, 2013) (Tserenpurev, 2012). Also, 18% of the country receives solar insolation at a rate 4.5-5.5 kWh/m^2 per day during the year, and 2600-2900 hours of sunshine per year (Secretariat, 2013) (Komoto, 2013). Solar energy is a suitable source for rural areas (Secretariat, 2013). Today the herdsman households use mobile solar PV system for lighting, television, and dish for the television, radio, freezer, and fridge (Secretariat, 2013). Mobile PV system is not enough to meet herdsman households' energy demand due to the PV panel and storage is small and the current technology applied is deteriorated. Below *Figure 4* illustrates the solar energy resource of Mongolia where solar energy potential is decreasing from south to north. Mongolian thermal solar system is expected to have the potential to provide domestic hot water demand (Laughton, 2010). However, for heating in Mongolian cool climate season, the merely a thermal solar system is not sufficient and which is required to be complemented by other heating sources (Hausladen, 2012) (Secretariat, 2013) (Laughton, 2010) (Tserenpurev, 2012) (Boyle, 2004).

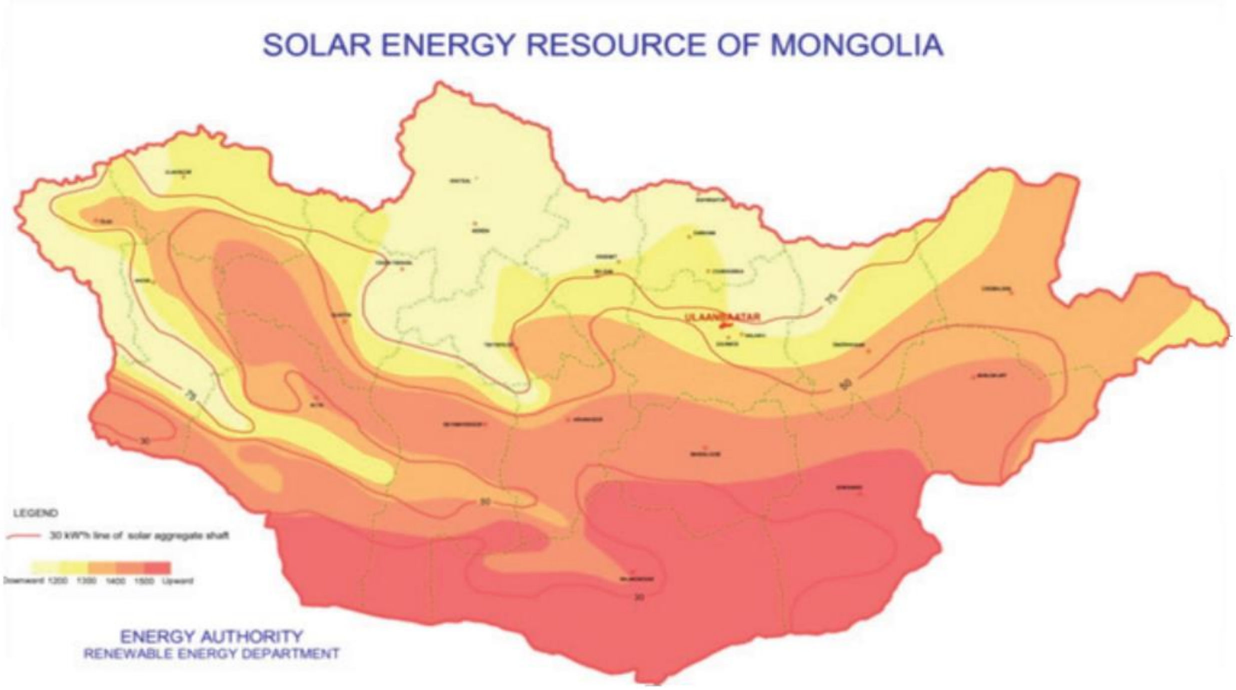


Figure 4: Solar energy resource of Mongolia (Secretariat, 2013).

The recent progress in solar energy technology provides the opportunity for herdsman households to support their energy demand. The solar panels which are flexible and lightweight forms are suitable as it should meet transportable (Pagliaro Mario, 2008). In the below Figure, the example of a flexible solar panel is shown which is supported with the waterproof material (Pagliaro Mario, 2008). The flexible solar cell is thin and lightweight (25-50g/m^2), and unbreakable as it doesn’t contain a class component, that is a very big opportunity for the nomadic lifestyle. The yurt roof is friendly to set up the solar PV system because the roof slope angle is approximately 30°

1.5. Literature review for the nomadic vernacular architecture

1.5.1. Literature review of the Mongolian yurt, related paper: A review and systemization of the traditional Mongolian yurt (Ger)

One of the ancient structures made by mankind is the yurt which is still used in contemporary living for Mongolians and some other countries. In the nomadic cultural countries around the world, the yurt shelter forms a basic vernacular architectural style (Banzragch, 2006) (King, 2001) (Kemery, 2006) (Bayarsaihan.B, 2006). The basic round shape of the yurt has not evolved for the thousands of years that the structure is set to be portable with a collapsible wooden frame which can be assembled in a few minutes. The Mongolian yurt module is set up by the dimensions of crown holes for the poles (Banzragch, 2006) and the size of the yurt associates with the size of the crown which usually holds the radius proportion of 4:1 (Banzragch, 2006) (Kemery, 2006). And the several parts of lattices make a circular wall which is bound to lintel doorway. As the traditional yurt has not changed significantly, thus in modern times still the yurt parts are made of organic and traditional materials including wood, the skin of the cow, yak, camel, horse, sheep wool and horse hair and tail which do not require any heavy processing. The wood sticks form the collapsible lattice walls and those are bound by the camel skin and this structure makes it strong, durable and easy to assemble (Bat-Ulzii.B, 2016) (X.Gao, 2009). The entire structure can be fully packed and transported by camel, yak and in modern days by a small car.

Review of the historical evolution of the yurt

The archaeological findings prove that yurt has been in use of humans for more than a couple of thousands of years in Mongolian steppe and the most recent expedition finds yurt drawings from

Mongolia (Banzragch, 2006). During the Hunnu empire existence, BC 4th to the 1st century, (which is the first nomadic empire located in current Mongolian territory and in some literature documented as Xiongnu), the yurt was used for living purposes as stated by Sy Machani in his book called 'Shi Ji'. People during that time used livestock animals in a very broad ways for their day to day life consumption including consuming meat for food purpose, applying the skin for clothing to covering the yurt (Banzragch, 2006) (Altangerel.M, 2001) (Guan X. W., 2006) (X.Gao, 2009) (Salvalai G., 2017).

In the book of Professor Daajav Banzragch, it is noted that several tribes of Hunnu Empire migrated to South, Indian region and parts of Europe due to severe winter followed by droughts in the summer and loss of the majority of animals around the 1st century (Banzragch, 2006). And this migration is conjectured as the start of spreading yurt around the world. After the era of the Hunnu Empire, the yurt was used by the next nomadic states of Xianbei, Tureg, and Uigar for their basic shelter (Banzragch, 2006) (Altangerel.M, 2001) (Chong.C.G, 2014). After that, the next findings related to yurt was in the era of Chinggis Khaan when he established the biggest Mongolian Empire in the 13th century, that the yurt was found to have developed into different types for adapting the local cultural and environmental factors. As well as the yurts were designed to fit for different purposes like the armies used different sizes of the yurt and the king and the queen's yurts were based on the carts powered by 33 oxen (Banzragch, 2006). The army general and soldiers' also had yurt while shifting to different territories and for which the carts were powered by a smaller number of oxen in between 3 and 11, and carts were used to protect the yurts during the nights as it becomes the barricade for the yurts.

Later, Abtaisain khan's (1554-1588) yurt base with 45m radius has found from Erdene Zuu, Kharkhorin, Uvurkhangai province of Mongolia which was built for the 300 people capacity and the base was built by stones and brick floorings with smoke pipes for heating (Altangerel.M, 2001). And the number of lattice walls during the 13-17th century is recorded as between 8 and15 which are comparably huge in relation to modern daily uses yurts (Banzragch, 2006). The yurt originally had felt the door and after the times it was changed to wood and the crown became compounded as the lifestyle was turned out to not moving far as shifting within the cities (Banzragch, 2006) (Bayarsaihan.B, 2006) (Bat-Ulzii.B, 2016).

Structures and materials of a yurt

The traditional yurt generally has two main parts, including a collapsible wooden frame and cover with sheep wool felt. *Figure 5* illustrated details of the traditional Mongolian yurt. The dimensions of all elements are defined by the module which is mainly the diameter of the crown.

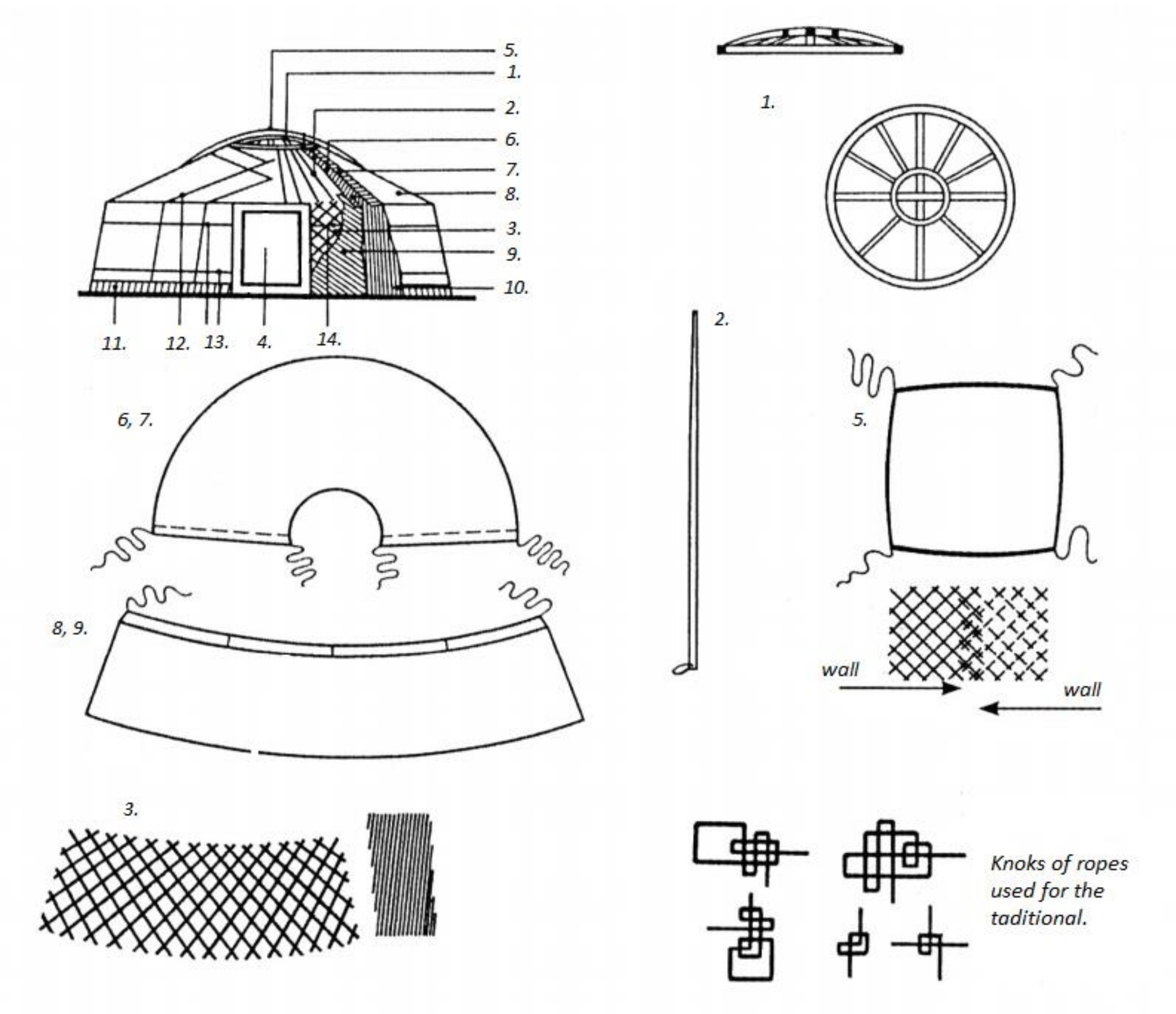


Figure 5: Materials of the traditional Mongolian yurt, wooden frame: 1. Toono-crown, 2.Uni-poles, 3. Walls, 4. Door. Felt cover: 5. Urkh, 6. Inside the felt roof, 7. Outside felt roof, 8. Coverage, 9. Inside felt the wall, 10. Outside the felt wall, 11. Khayaavch- felt or wooden boards closing off the lower edge of a yurt wall in winter, 12. Ropes, 13. Outside belt, 14. Inside the belt

Types of yurts

There are various types of yurts used around the world. The types are varied by their purpose: commercial, tourism and residential. It has found that 31 countries use yurts with different purposes as illustrated in *Figure 6* and out of which 13 of them uses their traditional yurt which are 10 types of the yurt shape. The climate of areas had a huge effect on changing the design and shape of the yurt and the basic form of the yurt has evolved for specific countries (Liu.H.Y, 2017).

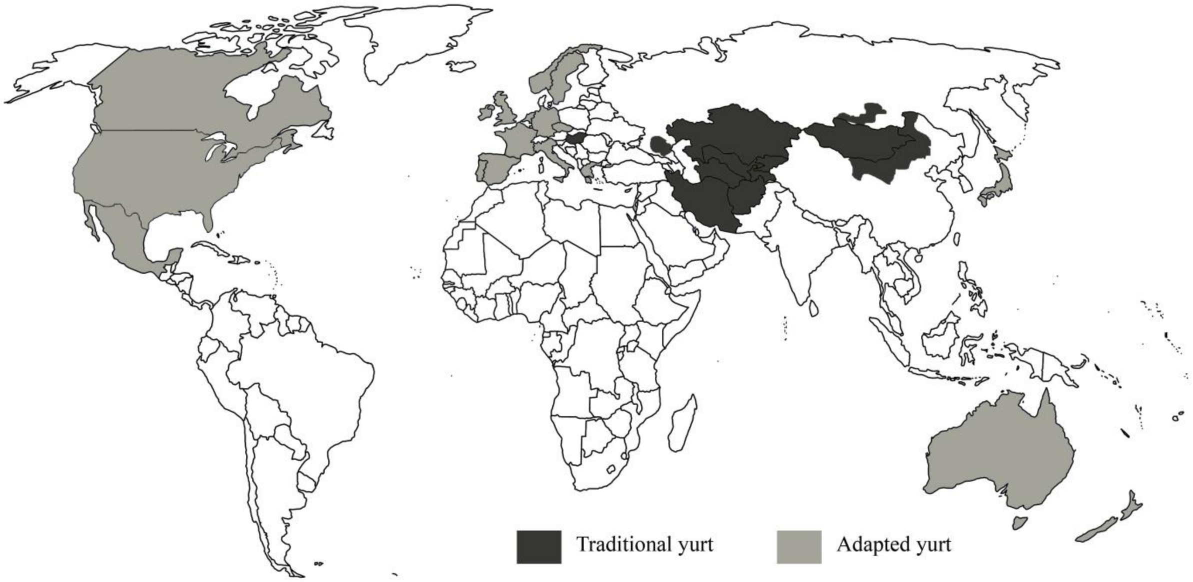


Figure 6: The location map of traditional and adapted yurt in use today.

The locally originated (Mongolian) yurt was developed by traditional means. And in the other countries from region to region alternative designs appear. In *Figure 8* the self-constructed analysis for yurt uses are shown, and the black highlighted countries use their traditional yurts for residential or historical purposes and those grey colored countries use adapted yurts for commercial purposes.

1.5.2. Literature review for the yurt in building physics

The number of studies covered building physics of the yurt is limited. One of the earliest and thoroughly studied similar shaped buildings to the yurt was "Dymaxion unit and Wichita House". After World War II, in 1940 Buckminster Fuller designed the dome-shaped small house in relation to tackling the housing shortage in the USA. For this small house, recycled metals of steel, aluminium, and Plexiglas were used. He calls the house as ‘Dymaxion House’ (M.J.Gorman, 2005) (K Mrkonijic, 2006). At the center of the house roof, he designed a hole which provides a function of ventilation rather than for heating (chimney) and for natural lighting (skylight) those related to general yurts.

The ‘Wichita house’ has some windows on the wall and had a rotating vent at the top, fitted with the rudder. The final design of the house used a central vertical stainless steel strut on a single foundation. The structures look similar to that of an umbrella.

Fuller studied natural ventilation of the house used by the wind tunnel analysis (*Figure 7*) (M.J.Gorman, 2005) (K Mrkonijic, 2006). The natural ventilation has worked very well. The ventilation is similar to the yurt as having high effect for the air changes which is called as “Dome chilling effect” (Bayarsaihan.B, 2006) (M.J.Gorman, 2005) (K Mrkonijic, 2006).

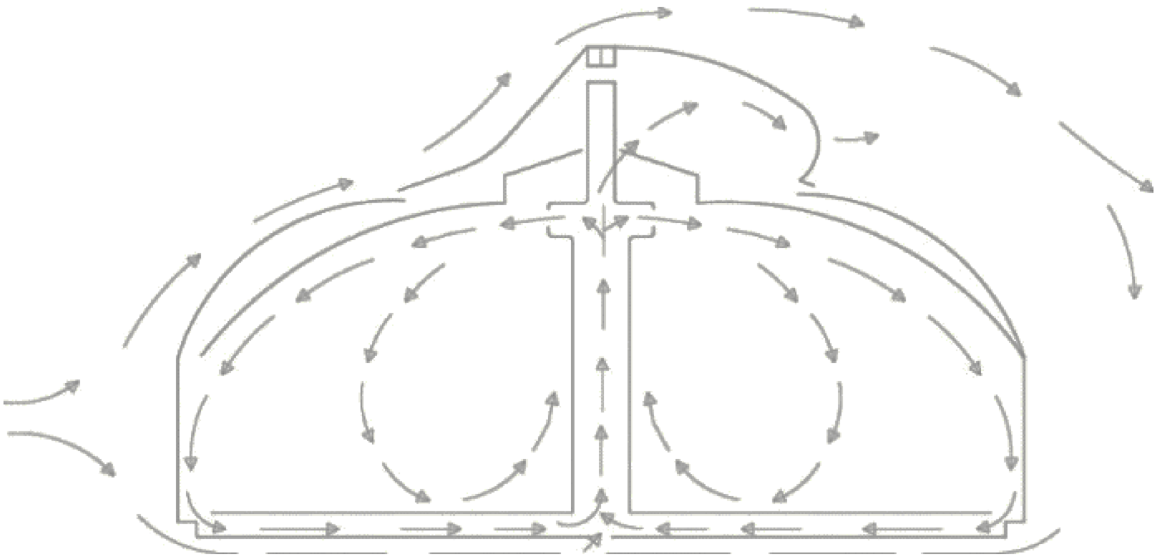


Figure 7: Dymaxion Deployment unit (Wichita house) (M.J.Gorman, 2005).

Heat transfer analysis of the yurt in simulation

The model results in heat transfer inside the yurt when the yurt warms up or cools down in the winter by the ‘lattice Boltzmann method’. The yurt cools down from the warm condition, the temperature differences near the crown and the door creates two cells of flow: the major cell develops continuously; another one activated by the major cell is pushed by the major cell and disappears eventually (Badarch, 2017). The two circulation cells transferring heat inside the yurt remain stable during the heating of the yurt from the cold condition. A time the yurt gets cold was 1.4 times slower than the yurt warms up. To slow down the heat losses from the crown and the door, innovative designs are significant. The heat-related innovations for the yurt improve air quality in the city and bring comfort for the nomads (Badarch, 2017) (Hong Yan Liu, 2017) (Xin Hong Zhang, 2017).

Measurement analysis of the yurt

The temperature difference between day and night could reach 15 ºC in the transitional season and 10 ºC in the winter season and the indoor temperature change was almost synchronous with the outdoor temperature change. Since felt is a hygroscopic material, it can adjust the indoor humidity when the outdoor humidity fluctuates greatly. When the outdoor humidity was low, felt would make the room drier (Guogiang Xu, 2019).

The indoor temperature distribution of the yurt was affected by the felt seams, the gaps between the door and wall felt, ground conditions, and solar radiation (Guogiang Xu, 2019).

The main influencing factor of the temperature of the yurt's inner wall surface was solar radiation, and the temperature of the inner wall surface in each direction changed when the direction of solar radiation changed. The temperature difference was less than 4 ºC when solar radiation was the strongest and less than 1 ºC when there was no solar radiation (Guogiang Xu, 2019).

The seams between different components of the yurt and the joint between the door and felt enclosures surrounding the wall greatly influenced the indoor temperature. The levels of cold air penetration at the joints were in the following order: 'joint between the wall felt and the ground is higher than joint between the top felt and roof felt joint between the wall felt and roof felt'. The levels of cold air penetration at the joints between the door and the wall were: 'lower part is higher than upper part, upper part is higher than middle part' (Guogiang Xu, 2019).

The top felt opening had the greatest influence on the indoor humidity. Opening the surrounding wall felt had the most obvious influence on the temperature (Guogiang Xu, 2019). A heat source could quickly raise the indoor temperature, but the temperature dropped rapidly after the heat source stopped working (Guogiang Xu, 2019).

The solar heating system which was installed on the yurt has 30% improved the heating energy of yurt in January and December, 40% improved the heating energy in February and November

(Sainbold S, 2013, translated from Mongolian). The yurt measured in the study has had the electric heating and solar heating system.

Conclusion of the literature review

One exception is Mongolia that all over the territory there still exists yurt living parts, including the capital city. On the basis of comprehensive literature and scientific paper research, a review is provided about architectural, structural, and material systematization of the yurt, creating a complete yurt-typology.

However, there is less research has found on building physics performance of yurt neither in professional nor in scientific publications. Therefore, there is a need for filling the gap in the literature with consideration of the physical performance of yurt with special regard to efficiency and environmentally conscious and comfortable design. As a result, the thesis aims to develop contemporary, sustainable, light weight-transportable housing solutions.

1.6. Research goals

To fulfil the objective, the following goals have set:

1. Review current literature on the transportable vernacular architecture and verify compatibility to Mongolian climate.
2. To find the optimal shape form of the yurt with the purpose of improving energy and indoor comfort, thermal dynamic simulations will be performed for different shapes of a yurt in Mongolian climate settings.
3. To identify the most efficient and comfortable yurt, a comparative analysis will be conducted for varying types of yurts. The yurt characteristics of opening, orientations, structural materials, systems and operation of the yurt will be analyzed in a thermal dynamic simulation tool.
4. Find the yurts with optimal characters from the simulation cases.
5. Collect the optimal characters and properties from the simulation cases and create a new yurt applying the collected data.
6. Developing an adapted, transportable, energy efficient and low tech solution, this meets modern architectural concepts.

7. To find the optimal transportable residential building in the extreme changes in climate zones, development of the traditional vernacular architecture, used by the validated professional thermal dynamic simulation tool with the high resolution of climate data.

1.7. Research questions

- Do current, traditional yurts provide indoor comfort, which meets the modern living standard of occupants?
- How can we develop a yurt in order to make it more energy efficient and comfortable in terms of thermal comfort and indoor air quality?
- How to achieve today's energy consumption and indoor comfort requirements in an existing yurt?
- What has to be changed, replaced, redesigned, and modified on a traditional yurt to develop a modern building development?

1.8. Research limitation

- The research specifically focuses on energy efficiency for the transportable building; therefore it might not be the best solution for the purpose of settling down in the same location for a long term.
- In the study, energy efficiency and those related materials are considered with priority; hence the economic and financial matters are not taken account.
- The research is conducted in only Mongolian climate zones and expected to be useful for other cool climate countries as Mongolian climate is one of the most severe and extreme condition.

1.9. Initial points of research

1. In the context of Mongolia, the yurt is used as the main dwelling for accommodation in terms of nomadic, movable lifestyle as well as a settled residential lifestyle which is related to the culture and tradition. The main structure of yurt satisfies the main functional need of being movable as well as livable. However, from the modern living standard point of view, the livability is diminished, as the comfort does not qualify for a high standard.

2. It is essential to maintain the main function of the portability of yurt. However, comfort as the complementary attribute to portability has been untouched and underdeveloped. The comfortableness concept involves massive characteristics, but the most impactful factors for Mongolian settings are deemed to be energy efficiency and indoor climate comfort.
3. Beyond the Mongolian and other nomadic country settings, the yurt has started to be used in other countries for travel, entertainment, and tourism purposes. For this hand, the enhancement in the comfortableness of yurt is demanded.

1.10. *Initial problems of research*

1. Mongolian climate has a significant temperature difference of 80 K between summer and winter.
2. So far, the nomadic and transportable building has not been studied from a scientific building physics point of view.
3. Through the centuries, the vernacular dwelling, the traditional yurt was developed mainly in terms of decoration and it has been changed in a minor renovation.
4. Today, 45% of total household live in a yurt and 29% of total yurts are not connected to the electricity supply system in Mongolia (Sovacool, 2011).
5. The yurt must maintain its transportability to fit for a nomadic lifestyle. Hence, it can’t apply complex building service systems and the potential considerations must include lightweight, fast and easy assembly properties.

2. RESEARCH METHODOLOGY

2.1. Literature review

As the initial research, the related literature on the transportable building, vernacular nomadic residential building will be reviewed, the literature on climate design of the transportable residential building in the cool climate zone will be reviewed and discussed.

2.2.Thermal dynamic simulation method

The main body of research will apply the thermal dynamic simulation method (Vepa, 2013) (Joseph, 2007). More specifically "Zonal simulation method" by the IDA-ICE simulation tool is applied (Baranyai, 2014).

2.2.1. Zonal simulation method

The zonal models refer to air models that use a three-dimensional grid to divide the the entire room into a system of control volumes (M. Lauster, 2014). Care should be taken to avoid confusing zone with zonal, where the former refers to traditional building zoning and the latter refers to one category of room thermal models. Zonal models are considered in more detail since there is a perception that they offer three-dimensional airflow models suitable for building load, energy simulation (A.Meslem, 1998) (Brent Griffith, 2011) (Haghighat & Yin Li, 2001).

Clearly, such research has demonstrated that it is possible to use pressure zonal models in load energy calculation programs. *Figure 8* illustrates the classification of the simulation models (Brent Griffith, 2011) (Haghighat & Yin Li, 2001).

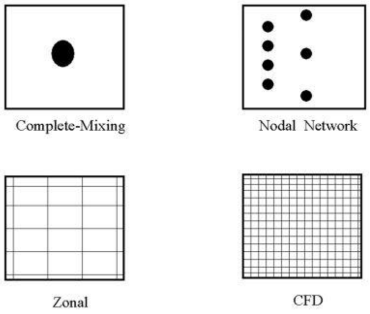


Figure 8: Classification of the simulation models (Brent Griffith, 2011)

Comfort: According to the zonal simulation method analysis the general thermal comfort including the Fanger's comfort index, operative temperature and humidity are analyzed (Christian Inard, 1996) (Ahmed Cherif Megri, 2007) (Stepham G. Warren, 1979). The dissertation focuses on the zonal thermal simulation due to the humidity in Mongolia is dry (Hausladen, 2012) (Zhiqiang Zhai, 2003)**.**

The basic idea of thermal comfort (FANGER) is: The human body has to keep the thermodynamic balance which makes the person feels the thermal comfort (Mohammad, n.d.) (Yang, 2014). The operative temperature involves the combination of air and surface temperature. The most comfortable operative temperature is between 20-24° C in the heating period and maximum 23-26° C in the cooling period for the normal residential building (Mohammad, n.d.) (Anon., 2004).

The thermal comfort applicable to the building is categorized in line with DIN EN 15251. In the below table, DIN EN 15251's 4 categories are shown. Out of the 4 categories, normal residential building refers to the II category in *Table 2.*

Table 4: comfort categories according to DIN EN 15251 (Anon., 2007).

Categories	Description
I	High level of expectations: recommended rooms with very sensitive people with special requirements, disable people, sick people, small children, and elderly people
II	Normal expectations: recommended for new and renovated buildings
III	Acceptable level of expectations: can be used in existing buildings
IV	Values not included in any other category. This category is used only for part of the year.

Source: DIN EN 15251

One of the measurements to gauge thermal comfort is Fanger's comfort which includes PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indicators in terms of DIN EN ISO 7730 standard. The standard has 3 categories of A, B, and C which corresponds to DIN EN 15251 (15251, 2007). And the residential building as categorized under II group in DIN EN 15251 matches B category of DIN EN ISO 7730. As illustrated in below table, PMV for the normal building is between the -0.5 to 0.5 and PPD should be less than 10% (*Table 2* and *Figure 3*), (Anon., 2007) (Anon., 2006).

Table 5: Classification according to DIN EN ISO 7730 and DIN EN 15251 (Anon., 2007) (Anon., 2006).

DIN EN ISO 7730			DIN EN 15251	
Categories	PPD	PMV	Categories	
A	<6%	-0.2<PMV<0.2	I	High
B	<10%	-0.5<PMV<0.5	II	Normal
C	<15%	-0.7<PMV<0.7	III	Moderate
	>15%	-0.7>PMV>0.7	IV	Outside

The relationship between PPD and PMV is shown through an empirical curve in below *Figure 9*. To meet the best condition, at least 5 percent of the population needs to be dissatisfied (Szokolay, 1997) (Leen, 2009).

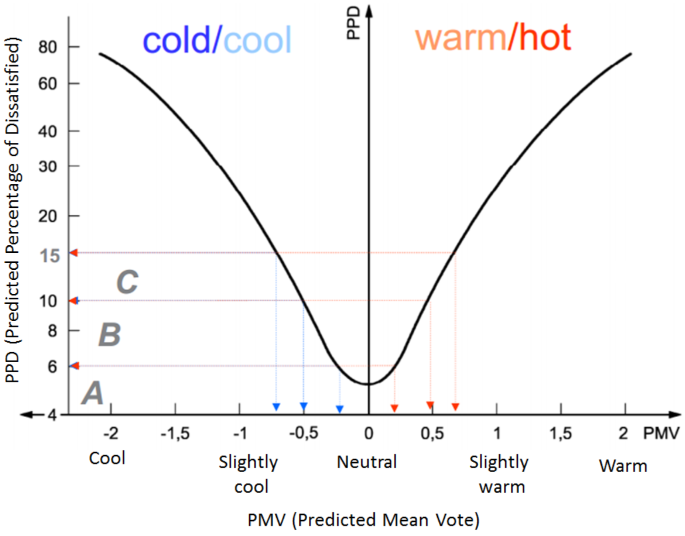


Figure 9: Predicted mean vote (note that at least 5% of any population would be dissatisfied even under the 'best' condition) (Szokolay, 1997) (Leen, 2009)

<u>Air quality:</u> The air quality and the amount of air exchange necessity within the building or its units are affected by emission produced by the appliances, the number of people and their activities. Carbon dioxide concentration level illustrates the pollution level. CO_2 adversely effects on the human body, imposing headache, decrease in performance, and potentially dizziness as oxygen transfer rate is reduced (Bauer Michael, 2009).

2.2.2. IDA-ICE

IDA Indoor Climate and Energy (IDA ICE) is a tool for building simulation of energy consumption, indoor air quality, and thermal comfort (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999).

The model of IDA ICE is written in the Neutral Model Format (NMF). NMF is a program-independent language for modeling the dynamical systems by using differential algebraic equations. IDA, on which IDA ICE is based, is a general-purpose simulation environment, which consists of the translator, solver, and modeler (Per Sahlin, 2003).

The library of the mathematical models of the building components was developed and tested for measurements and to other programs. IDA ICE may be used for the most building types for the calculations.

The full zone heat and moisture balance, including specific contributions from sun, occupants, equipment, lighting, ventilation, heating and cooling devices, surface transmissions, air leakage, cold bridges and furniture (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999).

- The solar influx through windows with a full 3D account of the local shading devices and those of surrounding buildings and other objects; Air and surface temperatures (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999).
- The operating temperature at multiple arbitrary occupant locations, in the proximity of hot or cold surfaces (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999).
- The directed operating temperature for the estimation of asymmetric comfort conditions and comfort indices, PPD and PMV, at multiple arbitrary occupant locations.
- The daylight level at an arbitrary room location, indoor air quality (CO_2, and moisture levels) network model.

This enables to study temporarily open windows or doors between rooms, the airflow, temperature, moisture, CO_2 and the pressure at arbitrary locations of the air-handling and distribution systems. The power levels for primary and secondary system components and the total energy cost based on time-dependent prices (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999).

Structure of IDA ICE

One or more zones define the building in IDA ICE. The different envelope parts (the roof, wall, and floor) separate the zones from each other and from the outdoors (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003). The envelope may include a number of openings, leaks, doors, and windows. Different heating, cooling, ventilation, and lighting systems can be attached to rooms (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003). Heat sources may involve: the heating/cooling device, air handling unit, envelope, direct sun through windows, leaks and thermal bridges, the internal thermal mass, occupants, lights, equipment. The moisture sources may be occupants, equipment, the air handling unit, envelope (external and separating), leaks, or other zones (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003).

The user has no direct control over the physical or mathematical model of the simulated system; Physical (Standard) level. The user uses the existing models taken from the library but has no direct control over the mathematical model (Per Sahlin, 2003).

2.2.3. Input data and boundary conditions for the simulation

Input climate data

The climate model is an algorithmic model that calculates and delivers the following data: the air, sky, and ground temperature, the air humidity ratio, air pressure, CO2-fraction, the direct normal and diffuse horizontal solar radiation, the wind direction and velocity, the elevation angle and the azimuth angle of the sun (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003). For the outdoor climate, IDA ICE uses two types of weather data: a synthetic design day or a climate file with measured data. The synthetic design day is based on the daily extreme wet and dry bulb temperatures, the wind direction and speed, and the reduction factor for the direct and diffuse sunlight. The weather file contains the information about the air (dry bulb) temperature, the relative humidity, the wind direction and speed, the direct normal radiation and diffuse radiation on a horizontal surface, all as a function of time (often in practice as hourly data). IDA ICE contains a separate translator for converting some of the established weather data to file formats (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003).

For the simulation, Tosontsengel station from the 1st climate zone was chosen, because it has the most extreme temperature difference and located in the north-west of Mongolia and highly elevated. In this area, the lowest peak temperature record was -53.0 ºC in 2006 and the maximum temperature was 33.8 ºC in August (Mongolia, 2004). Detailed graphic of climate data factors of the ‘Tosontsengel’ climate station from the ‘Meteonorm 7’, which are dry bulb air temperature, relative humidity of the air, wind speed, and sun radiation illustrated in *Figure 11*, *Figure 12*, and *Figure 13*.

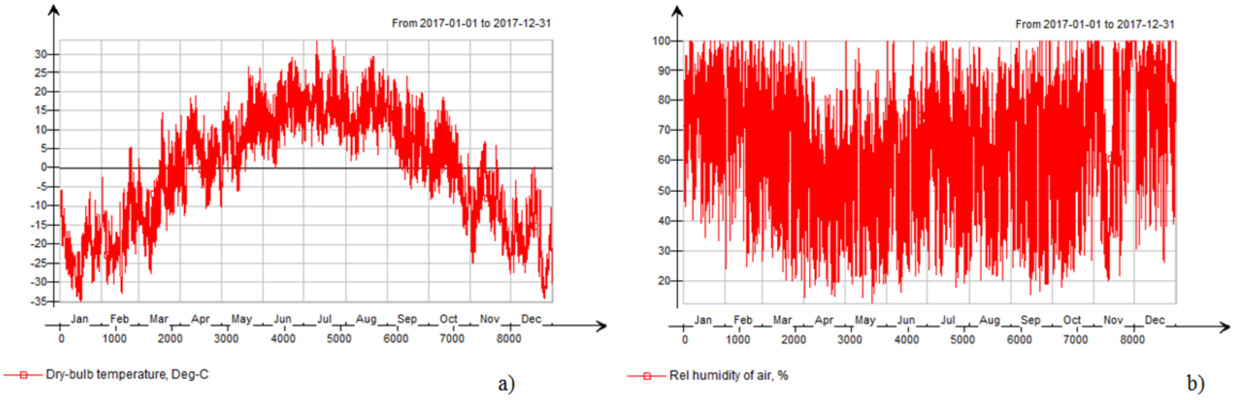


Figure 10: Climate data of Tosontsengel climate station from the ‘Meteonorm 7’ climate databank, a) Dry bulb air temperature [°C], (8760 hours), b) Relative humidity of air [%], (8760 hours).

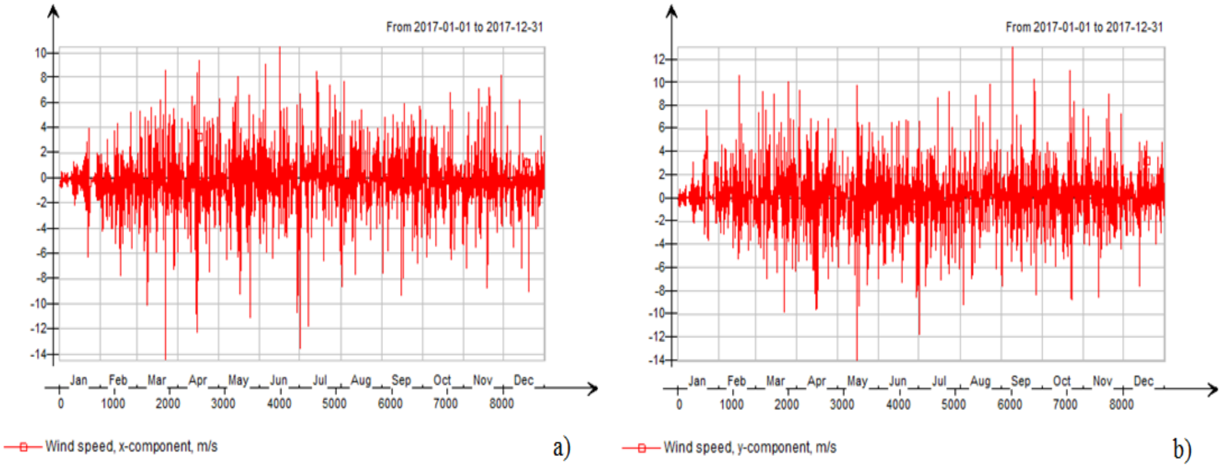


Figure 11: Climate data of Tosontsengel climate station from the ‘Meteonorm 7’ climate databank, a) Wind speed, x-component, [m/s], (8760 hours), b) Wind speed, y-component, [m/s], (8760 hours).

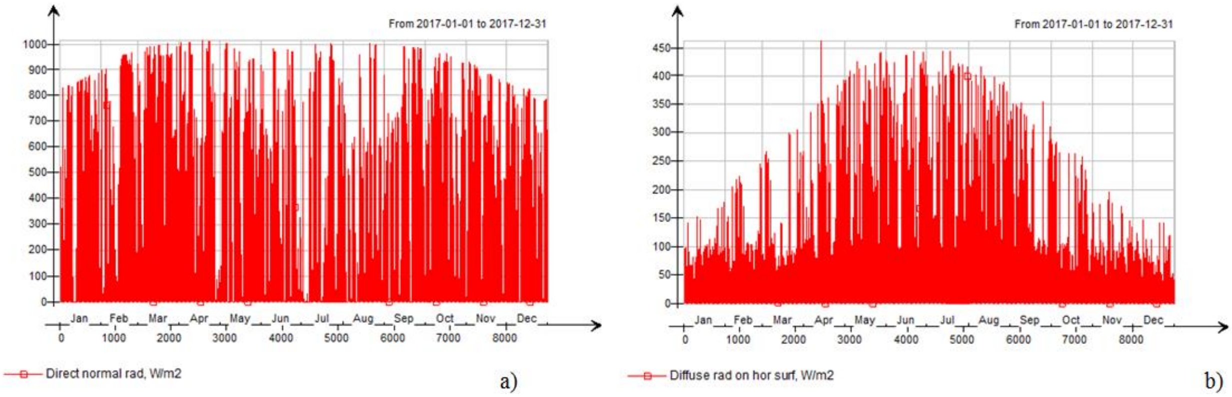


Figure 12: Climate data of Tosontsengel climate station from the 'Meteonorm 7' climate databank, a) Direct normal radiation, [W/m2], (8760 hours), b) Diffuse radiation on horizontal surface, [W/m2], (8760 hours).

After defining the appropriate geological location, a weather profile for hourly resolved 5 years average weather data was generated from the 'Meteonorm 7' climate databank (Remund, 2016) for the simulation. The nine differently shaped yurts gathered from existing and historical practice (Banzragch, 2006) (Bat-Ulzii.B, 2016) are built on the mathematical model, whereas there were similarities in between the shapes as all yurts' floor plan is round, has a central door and an opening on the top.

Input data for the model

For the all comparative analysis and development of the characteristics the same input data have used. The base yurt's area is 28m^2, volume and area ratio is a bit different due to the differences in the shape of the yurt.

Wind-driven infiltration airflow rate follows the structure materials at 50 Pa air pressure for all yurt models. Table 3 illustrated the thermal bridge of the yurt. Yurt's main thermal bridge is external slab and external wall.

Table 6: Thermal bridges of the yurt from the simulation input data

Thermal bridges	Area or Length	Avg. Heat conductivity	Total [W/K]
External doors perimeter	6.70 m	1.000 W/(m K)	6.697
Roof / external walls	24.32 m	0.850 W/(m K)	20.672
External slab / external walls	20.68 m	0.950 W/(m K)	19.642
Total	-	-	47.011

Climate model and boundary conditions

The zone model calculates the indoor climate. Two different zone models are included in the library: the detailed one is intended for design simulations and the simplified one for energy simulations (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003)**.**

To describe the location of a building the following data should be inserted: the latitude, longitude, height over the sea level, time zone, and the wind profile The calculated building can be shaded by surrounding buildings as well as the windows can be shaded by internal or external shadings (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003)**.** The external shading is controlled, for example, by the wind speed and solar radiation. The internal and external heat transfer coefficients are calculated by the model (Sven Kropf, 2001) (Kalamees, 2004) (Voulle, 1999) (Per Sahlin, 2003).

2.3.Comparative analysis.

A comparative analysis will be held for the different shapes of traditional yurts and which will be examined for Mongolian climate zones. For this analysis, the simulation tool will be applied to examine the energy and indoor comfort performance of the different yurt shapes with the same boundary conditions. The particular study will be discussed.

To contrast, the shapes of those nine types of yurts, the orientation of the yurts were set identical, and identical climate station weather data in a whole year period was applied (Radha Chro Hama, 2017). The floor areas are set same, albeit volume, ‘top’ opening, and door dimensions are different, following the shape form of the yurt. Under the material specifications, traditional materials of a wooden frame and felt (sheep wool) are considered in the simulations.

The more detailed comparative analysis on volume, envelope area, door, and opening area and Area ratio (Surface area divided by Floor area) (Banzragch, 2006) of traditional. The 13th-century Mongolian yurt shows the best results in the comparison, but the Mongolian yurt has shown the closest result to 13th-century Mongolian yurt *(Figure 13).* The best outcomes from each of the parameter are highlighted in grey as shown in *Table 8.* Regarding the set points, according to the yurt nature, ‘very poor’ criteria were applied for thermal bridges, ‘normal residential building’ criteria was applied to the opening and the door schedules, furthermore, the indoor mean temperature was set between 21 and 25 °C.

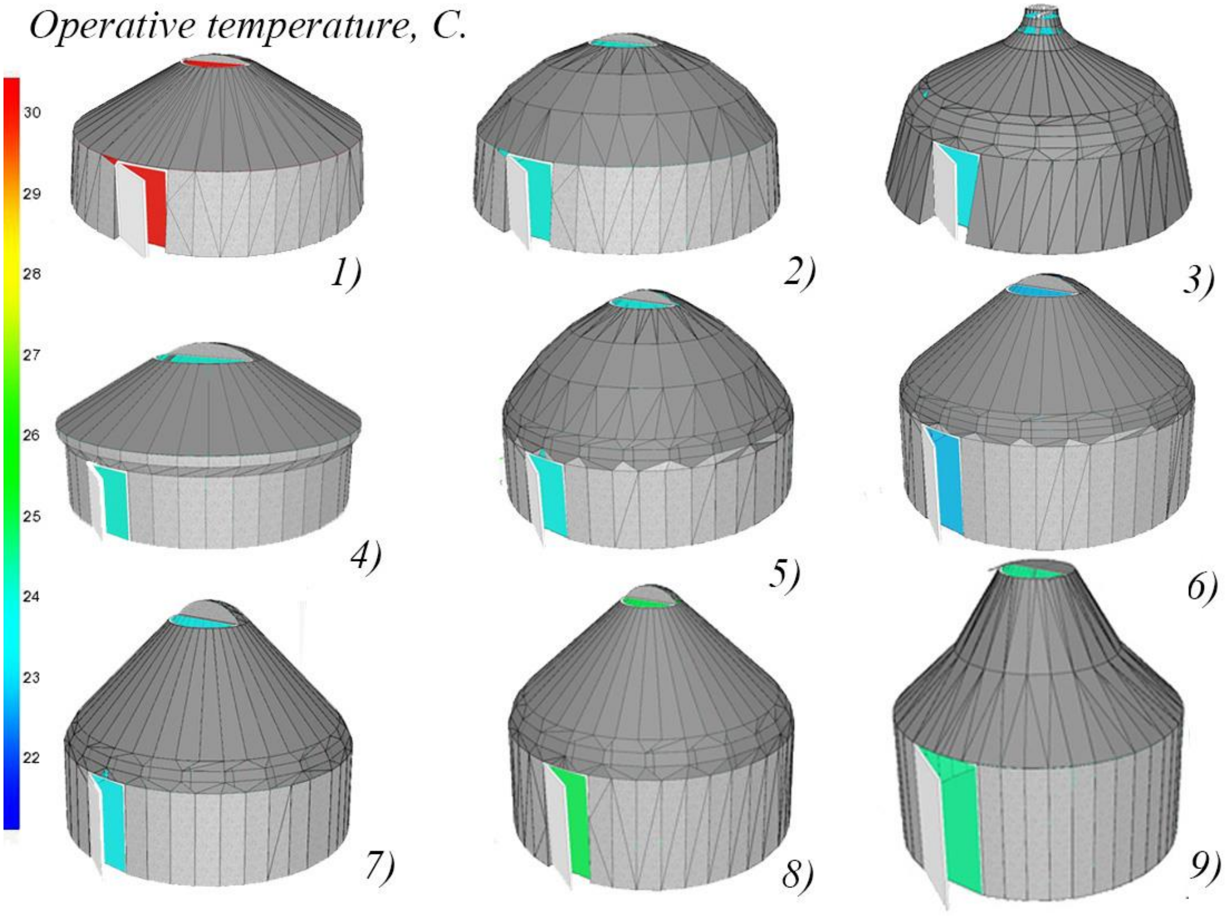


Figure 13: Dynamic thermal simulation models of different types of traditional yurts with indicated operative temperatures. 1) Mongolian yurt, 2) 13th-century Mongolian yurt, 3) Hunnu yurt, 4) Inner Mongolian yurt, 5) Hungarian yurt, 6) Kazakh yurt, 7) Kyrgyz yurt, 8) Double wall yurt, 9) Afghanistan yurt.

2.4.Optimal characteristics for the yurt development

As the initial point of research comparative analysis will be held for existing yurts and their components will be examined to find the best fit for a modern yurt. On the basis of results received from Comparative analysis, the traditional yurt will be developed through examining the different characteristics of other yurts and the best results for each characteristic will be combined to build the optimal yurt.

The previous studies discussed in new concepts on the transportable residential building will be designed. These concepts will be simulated for ensuring the prototype as an optimal solution by IDA-ICE simulation tool.

The key components considered for development are opening, orientation, structures and materials, and building services systems. Following steps have been conducted:

- The components are examined one by one to enable comparison
- The best component is selected shape the development study in terms of energy consumption and indoor comfort.

The development of the yurt has been used the characteristic which is Orientation (OR), Opening (OP), Structure materials (SM) and Systems (SY). All characteristics have been developing and compared to each other.

2.5. Research structure

In below *Figure 15*, the research structure is demonstrated in a diagrammatic form.

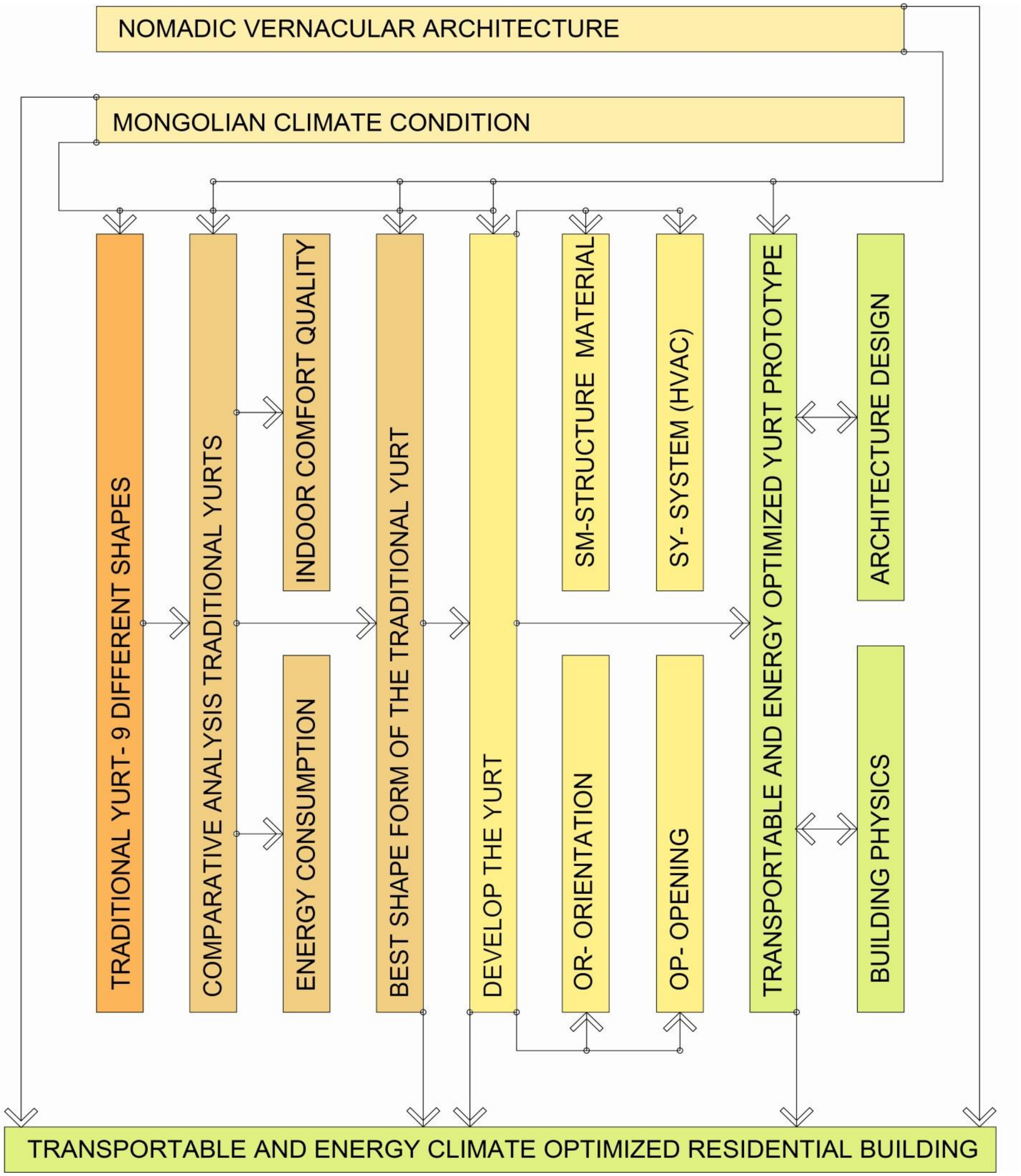


Figure 14: Research structure diagram for the topic.

3. *COMPARATIVE ANALYSIS OF YURT'S SHAPE, Related paper: Comparative analysis for traditional yurts using thermal dynamic simulation*

3.1. Introduction to the chapter

There are nine different types of traditional yurts around the world which are used in 31 countries, out of which 13 countries use its own traditional yurt (Banzragch, 2006) (Bat-Ulzii.B, 2016). In this study, IDA ICE 4.8 thermal dynamic simulation tool was applied and the mathematical model was built through simulating different versions of a yurt in conjunction with various climate zones of Mongolia. The purpose of the study is to find the optimal yurt shape in consideration of energy consumption and indoor comfort. Mongolia is one of the countries which have the hardest climate due to its huge temperature variance between winter and summer (Hausladen, 2012). Therefore we believe that the optimal yurt version fits for Mongolian climate can be also applied to varying climate zones of the world with slight or appropriate modification.

3.2. Simulation result evaluation

Detailed information on comparative analysis' result is shown in *Table 5* for each of the nine traditional yurts. The results include yurt dimensions of volume, envelope area, door, and opening area and A/V-ratio (envelope surface Area divided by Volume), S/F-ratio (Surface area divided by Floor area).

Table 7: General information on traditional yurts.

Yurt type	Floor area [m²]	Volume [m³]	Envelope area [m²]	Average U-value [W/m²K]	Door area [m²]	Opening area [m²]	S/F [m²/m²]
Mongolian yurt	28	50.3	82.8	1.374	1.38	0.83	1.96
Hunnu yurt	28	58.1	86.7	1.336	1.39	0.83	2.10
13th C Mongolian yurt	28	49.7	81.2	1.333	1.42	0.27	1.90
Inner Mongolian yurt	28	65.9	96.3	1.418	1.26	2.05	2.44
Hungarian yurt	28	78.9	100.6	1.339	1.53	0.87	2.59
Kazahk yurt	28	83.3	104.6	1.314	1.8	1.02	2.74
Kyrgyz yurt	28	82.1	103.6	1.366	1.93	1.02	2.70
Double wall yurt	28	95.1	112.5	1.315	2.36	0.54	3.02
Afghanistan yurt	28	108.6	128.3	1.363	4.53	0.95	3.58

The 13th-century Mongolian yurt shows the best results from the comparison, but the results are very close to 13th-century Mongolian yurt results. The best outcomes from each of the parameter are highlighted in grey as shown in *Table 3*. Regarding the set points, according to the yurt nature, 'very poor' criteria were applied for thermal bridges, 'normal residential building' criteria was applied to the opening and the door schedules, furthermore, the indoor mean temperature was set between 21 and 25 °C.

The comfort of the yurt

In this section, indoor air quality and thermal comfort will be analyzed through the facilitation of the simulation.

Indoor air quality

The result shows the bigger the volume, the lesser the CO_2 concentration in yurts, which proves that there is a negative relation between volume and CO_2. In *Figure 15* and *Figure 16* 13th century Mongolian yurt and Afghanistan yurt' CO_2 level is shown as a representation as they have the highest and lowest results, respectively. In the simulation, scheduling for top opening coverage is set as open for daytime and closed for nighttime, which effects to the yurt CO_2-level. Accordingly, CO_2-concentration increases in the night much higher than the approvable level in the standard (standard, 2014). Afghanistan yurt's higher volume effects as well as the CO_2-levels.

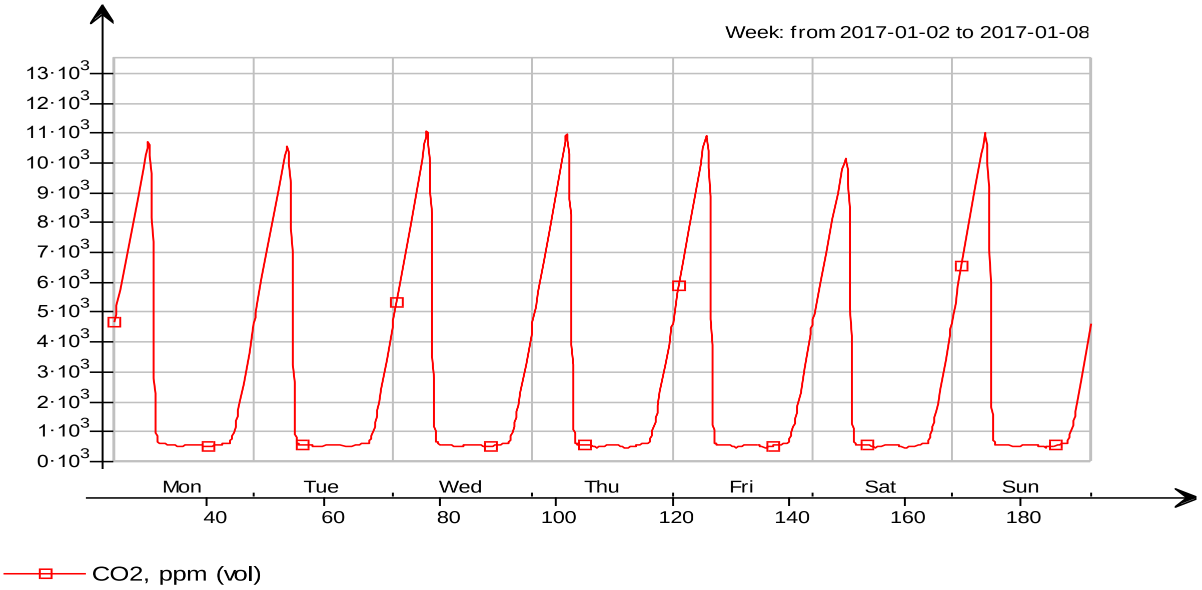


Figure 15: CO2, ppm of the 13th-century Mongolian yurt (8760h)

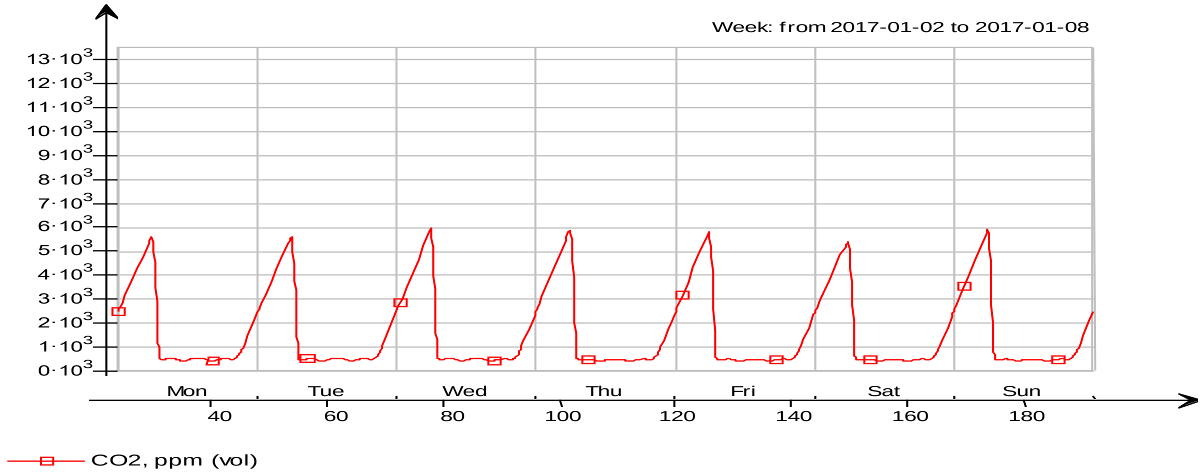


Figure 16: CO2, ppm of Afghanistan yurt (8760 h)

<u>*Thermal comfort according to EN 15251*</u>

Figure 17 shows thermal comfort from the best to the unacceptable category depends on the operative temperature and illustrated the numbers of the occupancy hours. The most thermal comfortable yurt is the 13th-century Mongolian yurt in consideration of its smaller results on a number of indicators including volume, envelope area, energy consumption, and heat loss in comparison to other traditional yurts.

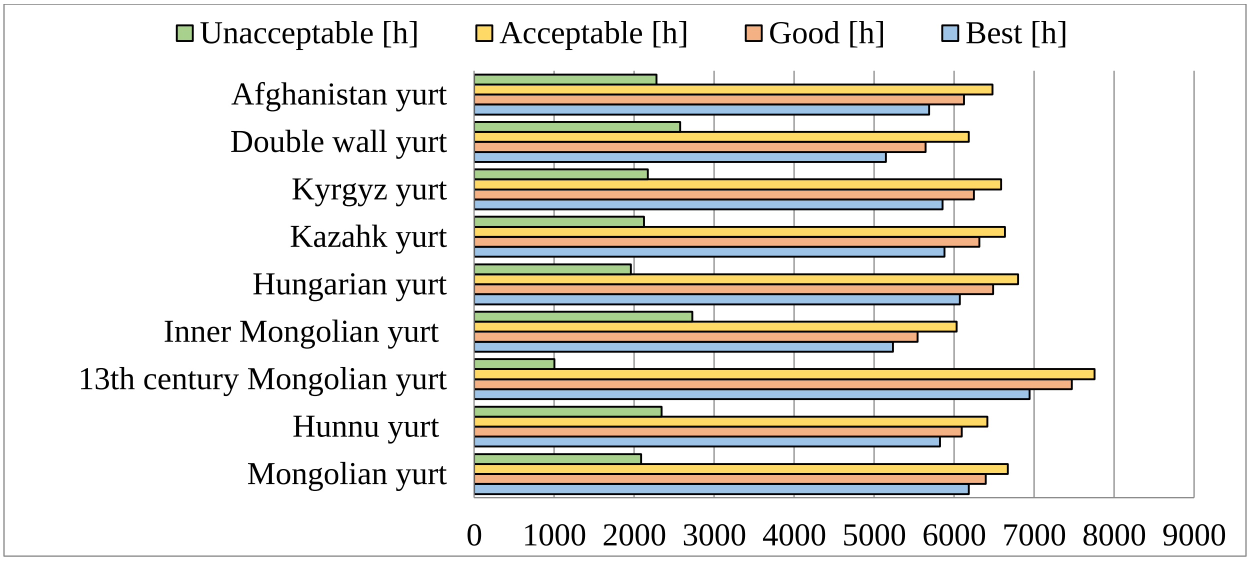


Figure 17: Thermal comfort category and numbers of occupancy hours.

The comparative result on the PMV (Predicted Mean Vote) is shown in *Figure 18 and Figure 19* the best-resulted yurt is the Hunnu yurt, a 13th-century Mongolian yurt, and Mongolian yurt is also good resulted in the simulation results but settled higher than the approvable level in the standard (Anon., 2006). Afghanistan yurt shows the highest variance on PMV because the PMV and the enveloped heat loss area, as well as the air change intensity, have a direct relationship.

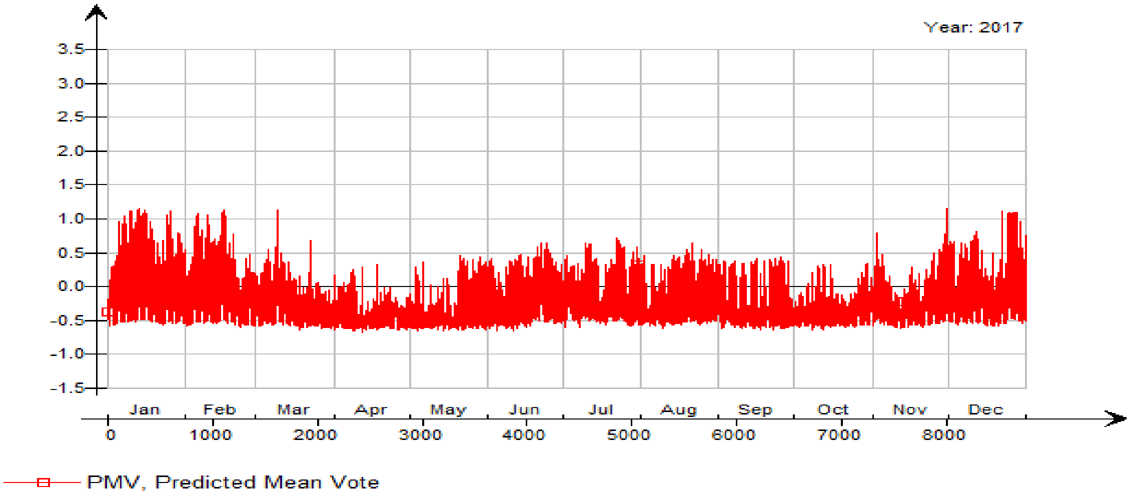


Figure 18: PMV, (Predicted Mean Vote) of 13th-century Mongolian yurt, (8760 h)

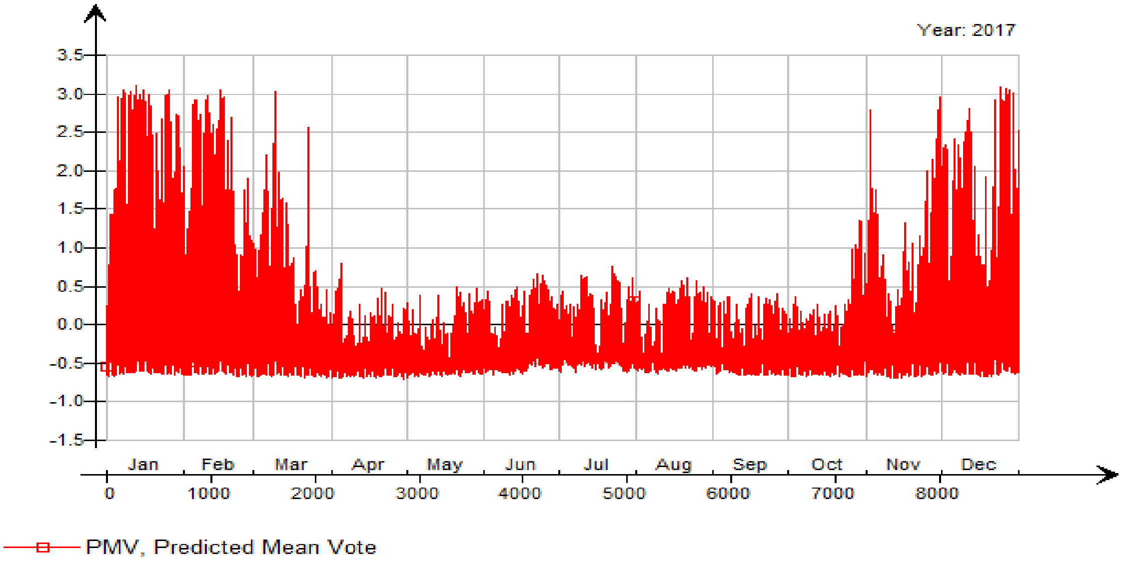


Figure 19: PMV, (Predicted Mean Vote) of Afghanistan yurt, (8760 h)

The energy performance of the yurt

The lighting (0.14 kW) and equipment (0.36 kW) show the same results in the simulation for all types of the yurt. As illustrated in *Figure 20* and *Figure 21*, 13th-century Mongolian yurt shows the best result in system energy.

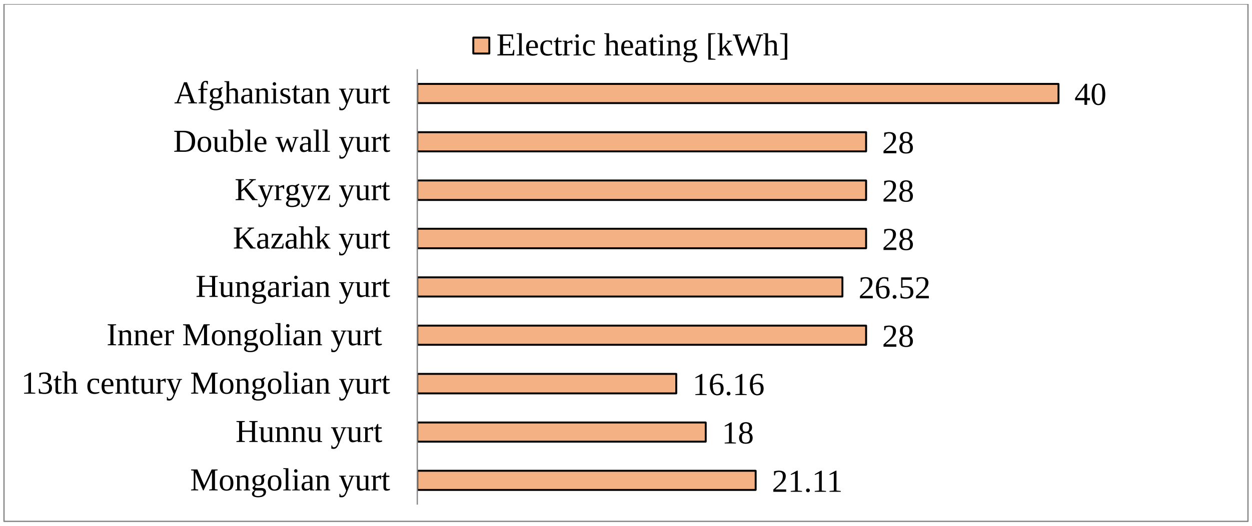


Figure 20: Used heating demand in the system energy of traditional yurts.

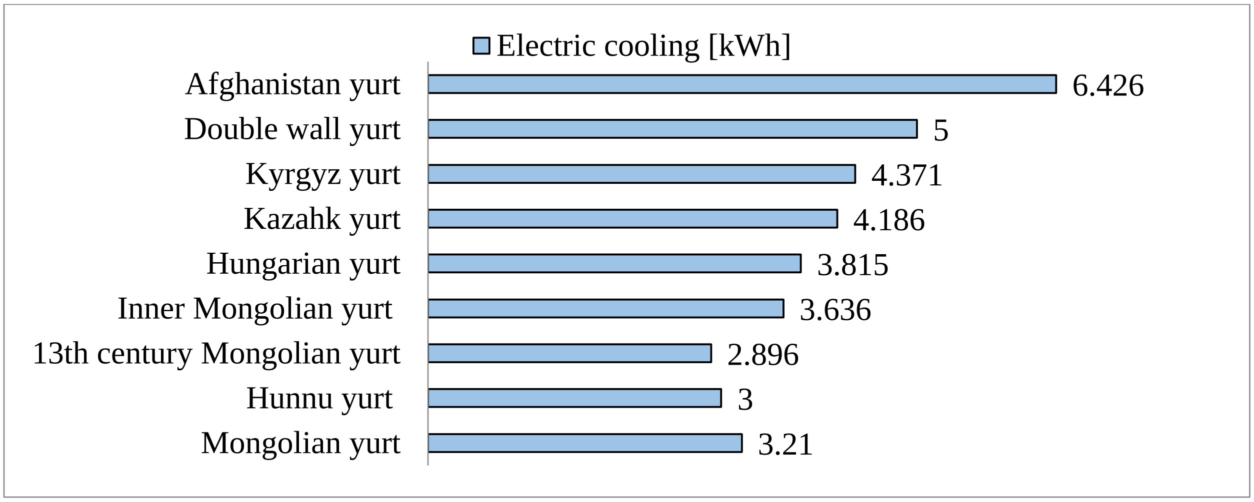


Figure 21: Used cooling demand in system energy of traditional yurts.

The delivered (purchased) energy of traditional yurts is shown; also the best energy consumption which is the best results for heating (*Figure 22*) and cooling (*Figure 23*) energy were performed in a 13th-century Mongolian yurt and in Mongolian yurt respectively. The 13th-century Mongolian yurt and Mongolian yurt are slightly different in the general shape information in *Table 7*. However, the two yurts are significantly different for the delivered energy result due to heating and cooling which depend on the size of the top opening.

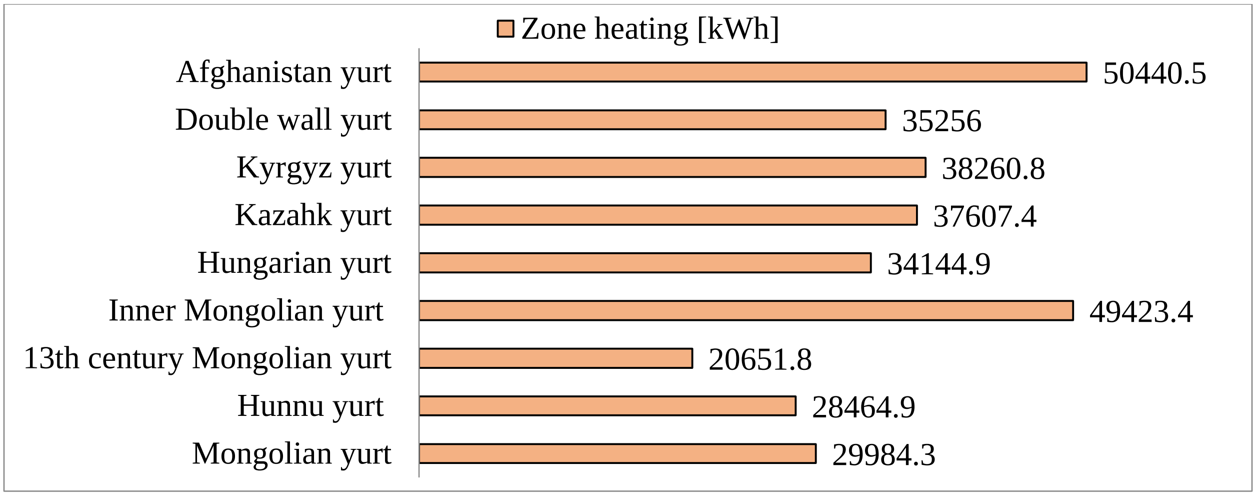


Figure 22: Zone heating in the delivered energy of traditional yurt.

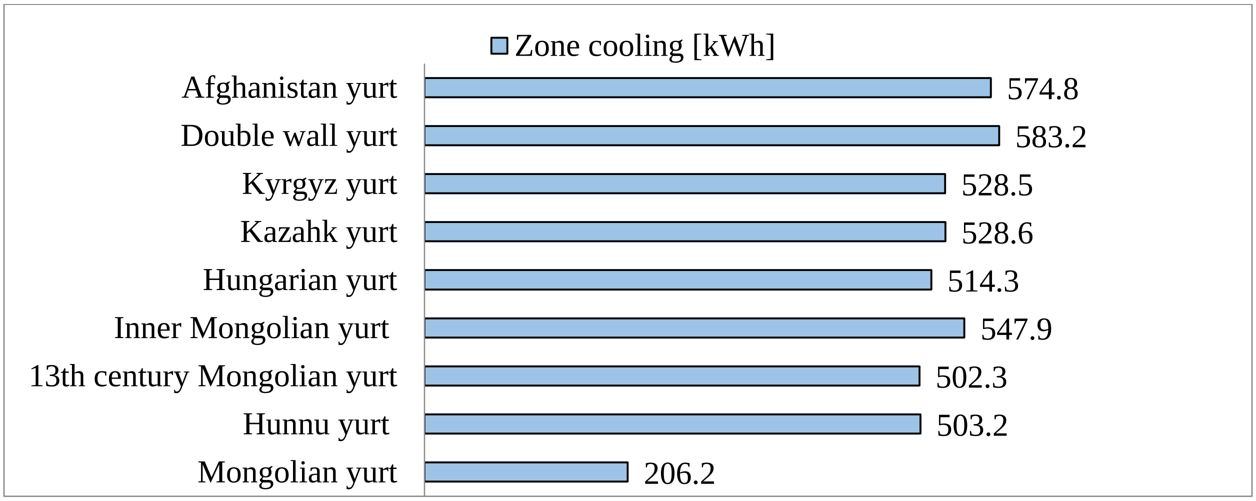


Figure 23: Zone cooling in the delivered energy of traditional yurt.

As illustrated in *Figure 24* under the total heat loss indicator, Afghanistan yurt shows the largest and 13th Mongolian yurt shows the smallest result. The heat loss from the envelope and thermal bridges appear in between 34.1 and 51.5% heat loss from the opening are from 10.7 to 50.9%. In respect to envelope and thermal bridges, Afghanistan yurt shows the highest heat loss and referring to infiltration and openings the Inner Mongolian yurt shows the highest heat loss. In the summertime, envelope and thermal bridges and top opening and infiltration provide cooling effect and Afghanistan yurt has the biggest envelope area.

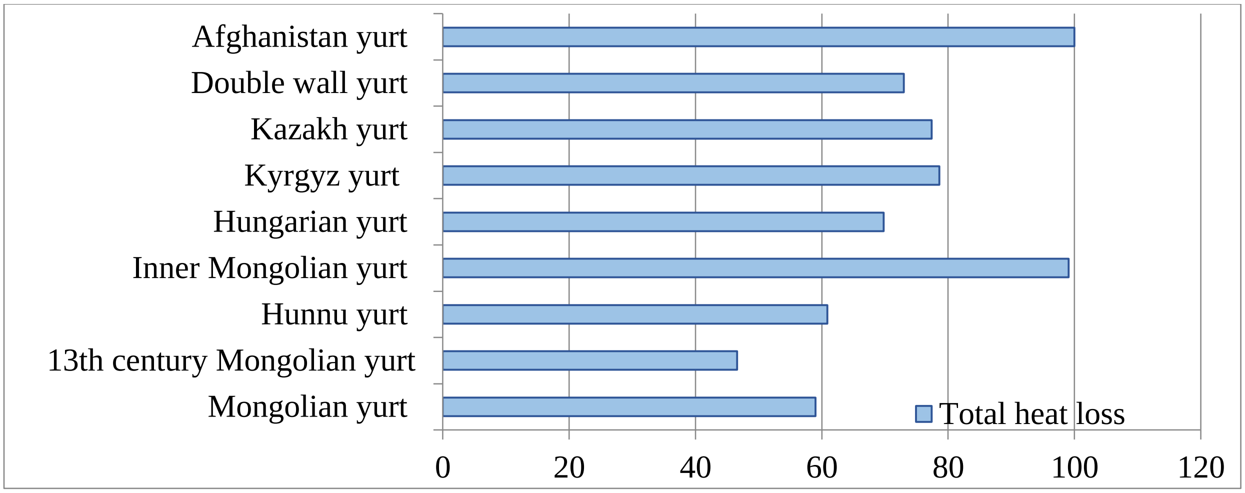


Figure 24: Percentage of the total heat loss through the yurt.

3.3. Conclusions: determining the most efficient vernacular yurt version

In this study, the nine differently shaped yurts are simulated in the climate settings of Mongolian extreme conditions. However, to support the comparative analysis, the yurts' round plan is set identical and depending on the shapes the volumes differ. The study examines the energy and comfort as part of the research on finding optimal yurt for Mongolian condition. The simulation shows varying results depending on the criteria. Regarding surface/floor area, the 13th-century Mongolian yurt is best, followed by a Mongolian yurt with a trivial difference. Also, 13th-century Mongolian yurt shows best results on system energy and delivered energy for heating. For cooling, the Mongolian yurt shows the best result as it has a bigger top opening than 13th-century Mongolian yurt. The top opening helps the cooling by the ventilation. The greatest heat loss is obtained in the envelope and thermal bridge losses in all the models, while the second amount of the heat loss is generated by the top opening. In the summertime, these help the cooling.

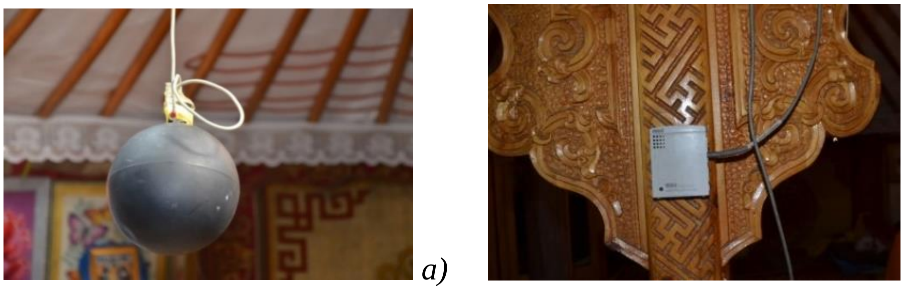
The CO_2-level of the yurt corresponds to the top opening schedule, during the night the top opening is covered and the CO_2-level exceeds an acceptable level. The top opening has a crucial role in ventilation.

In consideration of thermal comfort, all yurts show lower than the acceptable level under PMV results, however, 13th-century Mongolian yurt better results in comparison to others. In general, 13th-century Mongolian yurt has better energy consumption and is more comfortable than other yurts in the settings of Mongolian climate. On the basis of this study, it has found that there is a room for improvement in modern Mongolian yurt from the angles of energy consumption and comfort. In the future researches, 13th-century Mongolian yurt will be considered as the basis for further developments in accordance with its best results revealed by the current study.

4. STUDY OF ENERGY CONSUMPTION AND COMFORT FOR THE EXISTING TRADITIONAL YURT

4.1. Energy and temperature measurement of the yurt, Related paper: The study of measuring the thermal and energy consumption of the Mongolian yurt

Throughout an entire one year period, as part of the yurt study, the measurements to gauge the air temperature, radiation temperature, and energy consumption are installed with an hourly resolution. The yurt was located in the Songinokhairkhan district, Ulaanbaatar, Mongolia. The study has conducted between 2nd of October 2017 and 2nd of October 2018. Figure 25 illustrates the measurement tools of the radiation temperature (a), and air temperature measurement (b).



a) *b)*

Figure 25: Measurement tools for the yurt a) Radiation temperature measurement, b) Air temperature measurement (HOBO)

Air temperature measurement tools have been installed in different positions and different heights (*Figure 26*).

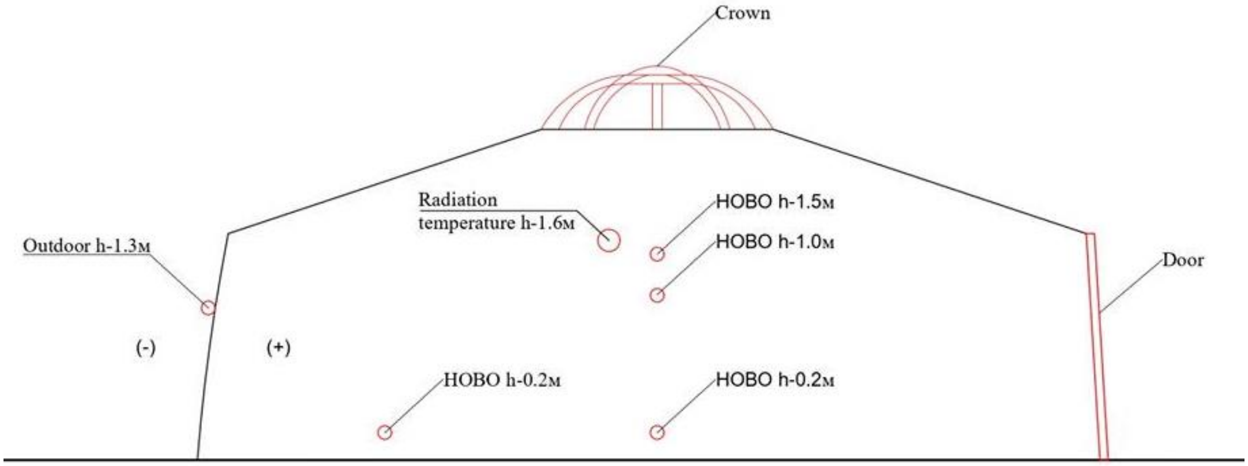


Figure 26: Locations of measurements.

Materials of the measured yurt

The studied yurt has double layered felt, water insulation, and tarpaulin. The floor is a 100mm concrete floor without insulation material. *Table 6* shows elements of the yurt and materials, the thickness of the material and area of the material.

Table 8: Elements of the yurt, materials, thickness of the materials, an area of the materials

Elements	Materials	Thickness [m]	Area [m2]
Wall	Water insulation	0.002	32.2
	Tarpaulin	0.002	33.2
	Felt	0.02*2	34.2
Floor	Concrete	0.10	35.2
Roof	Tarpaulin	0.002	30.6
	Felt	0.02*2	30.6
Door	Wood	0.06	2.7
Crown	Wood	0.06	2.2

Occupants and Equipment

The yurt has two occupants who are Mr. Balgansuren.T and his grandson. In below, *Table 7* shows the equipment of the yurt. In *Table 7* illustrated equipment of the measured yurt.

Table 9: Equipment of the measuring yurt

	Equipment	Amounts	Power [kW]	Total power [kW]
1	Television	1	0.114	0.114
2	TV rooter	1	0.02	0.02
3	Fridge	1	0.152	0.152
4	Freezer-1	1	0.13	0.13
5	Freezer-2	1	0.095	0.095
6	Cooktop with oven	1	3.5	3.5
7	Water boiler	1	3	3
8	Washing machine	1	1.3	1.3
9	Rice cooker	1	0.82	0.82
10	Electrical air heater	2	2.1	4.2
11	Lighting	1	0.1	0.1
	Total			13.43

The main source of the heating used for the yurt was two electrical air heaters which each has 2100W power. For the heaters, separate electrical measurement has been installed. In Table 6 shows the energy consumption of the yurt. The energy consumption of equipment and lighting is 2200kWh during the year and monthly average energy consumption is 183.3kWh.

Table 10: Energy consumption for the measured yurt

Meter	Total, kWh	Per m2, kWh/m2
Equipment, tenant	2200	62.8
Electric heating	10013.2	286.1
Total	12213.2	348.9

In *Figure 27* and *28* illustrated outdoor air temperature data for the January and July, which are the coldest and hottest month of the year.

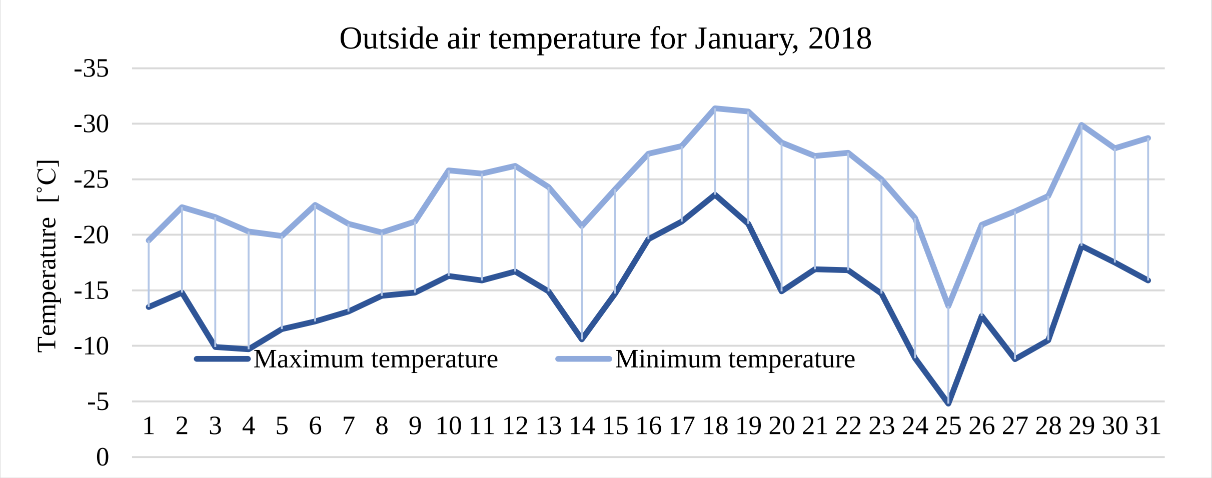


Figure 27: Outdoor air temperature for January. 2018

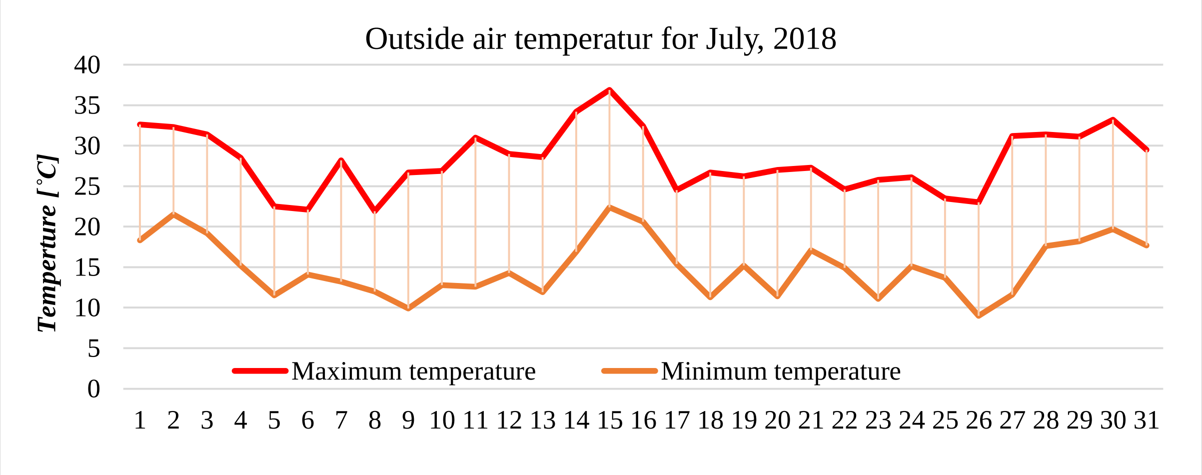


Figure 28: Outdoor air temperature for July 2018

In *Figure 29* illustrated daily average indoor temperatures for the measured yurt.

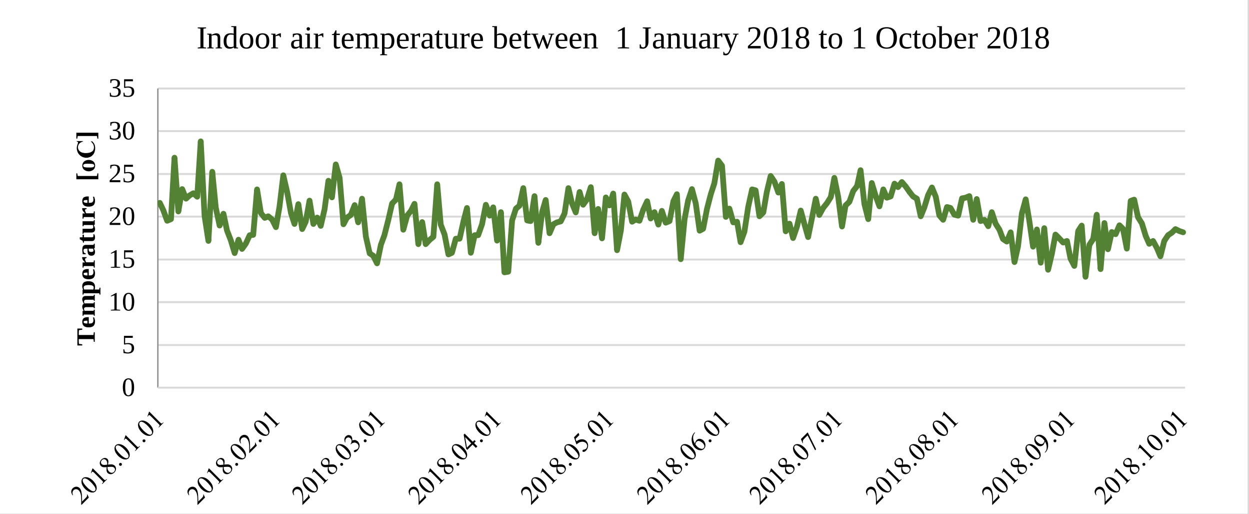


Figure 29: Indoor air temperature between 1st of January to 1st of October

In below Figure 30 illustrated the indoor air temperatures gauged from the measurement tools which were located in different positions and different height in the yurt. The yurt's air temperature is much different for the different heights. The yurt is very fast heat up during the heater is power on but without the heater, the yurt is also fast cool down.

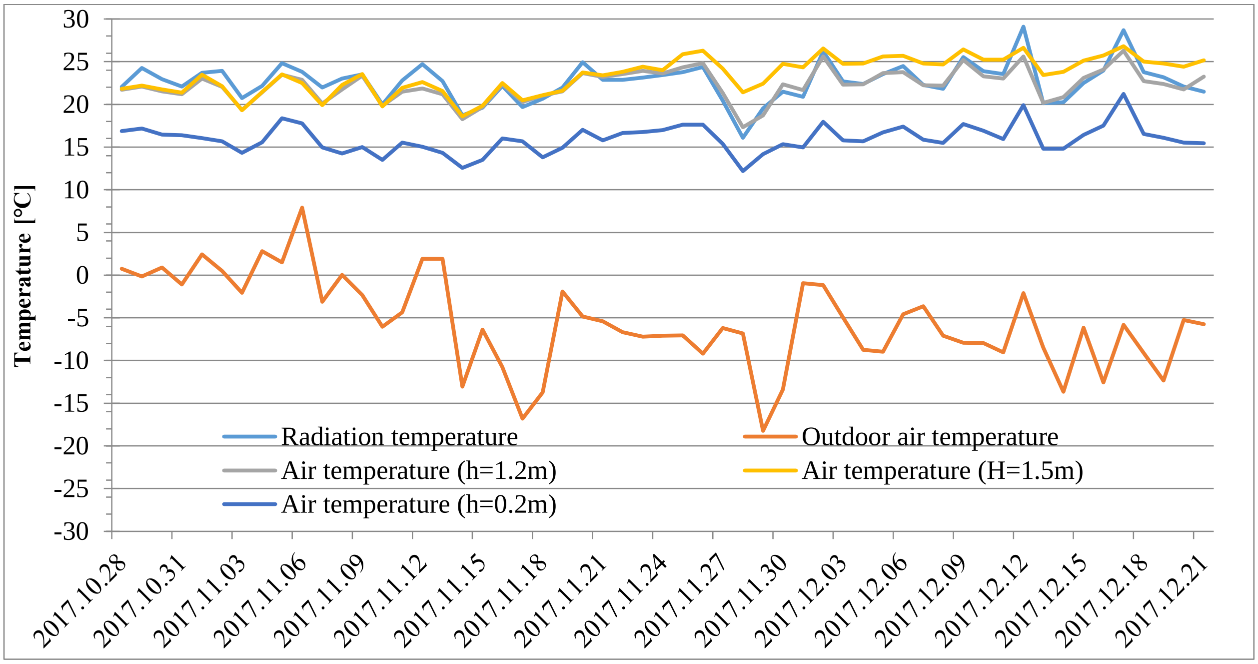
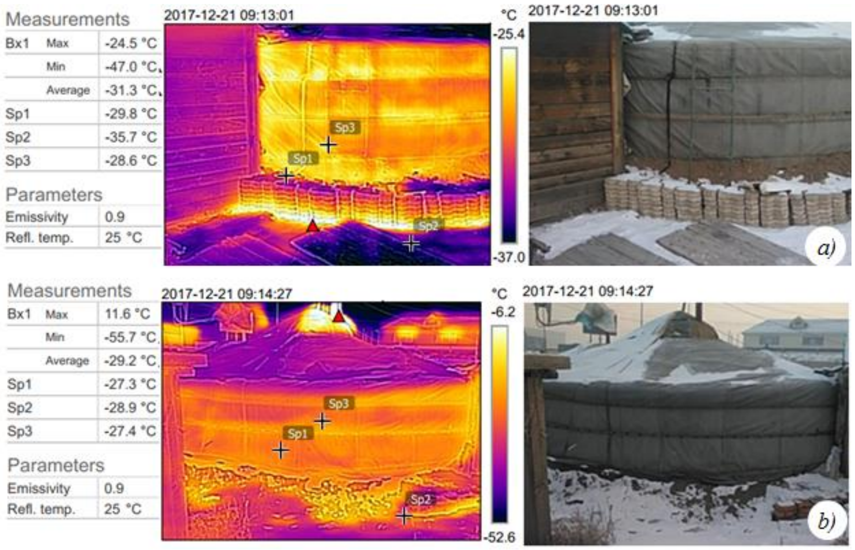


Figure 30: Radiation temperature, outdoor temperature, and indoor temperature of the yurt.

In below *Figure 31* illustrated the thermal photos of the measured yurt in the winter time. As shown in *Figure 31*, the minimum temperature of the outside of the yurt is too low on outside air and soil surfaces. The heat loss of the yurt through the crown is shown in *Figure 31-b.*

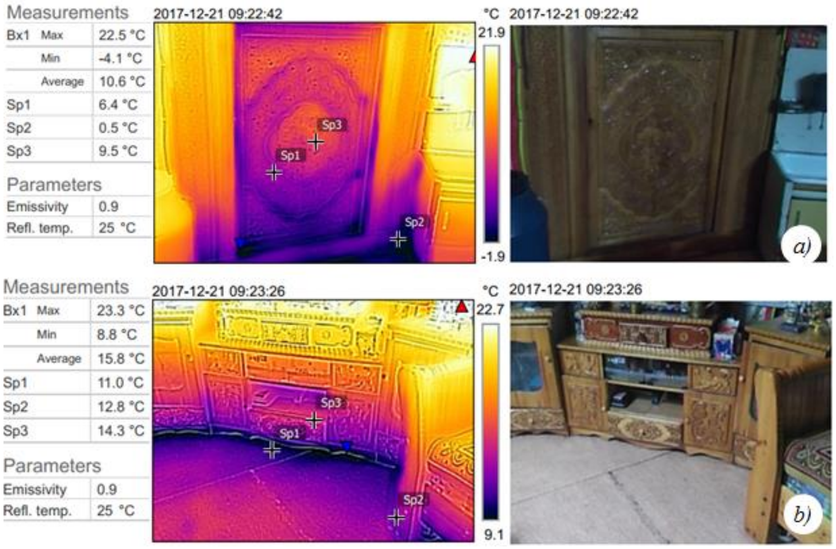


Measurements		
Bx1	Max	-24.5 °C
	Min	-47.0 °C
	Average	-31.3 °C
Sp1		-29.8 °C
Sp2		-35.7 °C
Sp3		-28.6 °C
Parameters		
Emissivity		0.9
Refl. temp.		25 °C

Measurements		
Bx1	Max	11.6 °C
	Min	-55.7 °C
	Average	-29.2 °C
Sp1		-27.3 °C
Sp2		-28.9 °C
Sp3		-27.4 °C
Parameters		
Emissivity		0.9
Refl. temp.		25 °C

Figure 31: Outdoor photo of the yurt a) From the south, b) From the north.

In *Figure 32,33* show the indoor thermal photos. The main heat is lost through the lower edge of the yurt's wall and door. Also, significant heat is lost through the crown as there is no insulation materials are attached to the crown.



Measurements		
Bx1	Max	22.5 °C
	Min	-4.1 °C
	Average	10.6 °C
Sp1		6.4 °C
Sp2		0.5 °C
Sp3		9.5 °C
Parameters		
Emissivity		0.9
Refl. temp.		25 °C

Measurements		
Bx1	Max	23.3 °C
	Min	8.8 °C
	Average	15.8 °C
Sp1		11.0 °C
Sp2		12.8 °C
Sp3		14.3 °C
Parameters		
Emissivity		0.9
Refl. temp.		25 °C

Figure 32: Inside thermal photo of the yurt, a) Door, b) North side wall

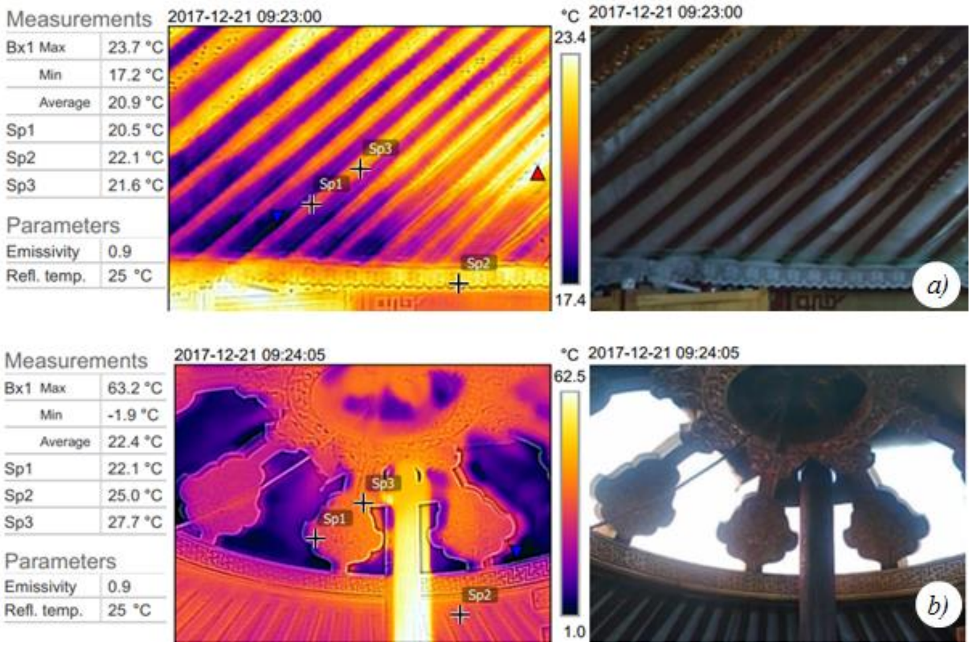


Figure 33: Inside thermal photo of the yurt, a) roof, b) crown

4.2. Energy consumption of the traditional yurt

Below *Figure 34* illustrates the thermal model of the mean temperature graphic of the 13th-century Mongolian yurt. The model's boundary conditions were set to the real conditions of the existing yurt. The yurt has 3 layers of the insulation coverage on the envelope (Roof and wall) with U-value is 0.9736 W/(m^{2}K).m.

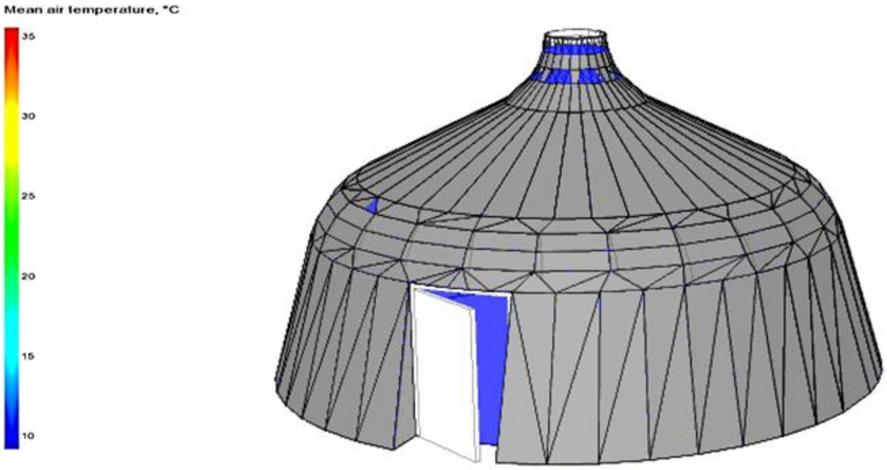


Figure 34: 13th-century Mongolian existing yurt

The heating and cooling system energy and delivered the energy of the 13th-century Mongolian yurt is described in *Table 9*. The total delivered energy includes lighting, facility and equipment energy.

Table 11: Delivered energy for the 13th-century Mongolian yurt (Heating and cooling)

Meter	Total, kWh	Per m2, kWh/m2	Peak demand, kW
Lighting, facility	306.5	10.94	0.14
Electric cooling	130.2	4.647	0.3001
Electric heating	10420.5	372	5.393
Equipment, tenant	3153.3	112.6	0.36
Total	14010.5	500.187	6.1931

In *Table 10* heat balance on envelope & thermal bridge, window & solar, and infiltrations & openings of the 13th-century Mongolian yurt are shown. The heat is found to be lost the most from the envelope & thermal bridges as illustrated in the below Table. The window & solar energy balance (transmission losses and gains and solar gains) shows heat gain from solar radiation during cooling and rest of time. Because the traditional yurt has no window at the wall, instead of top opening and door provide the function.

Table 12: Heat balance of the 13th-century Mongolian yurt

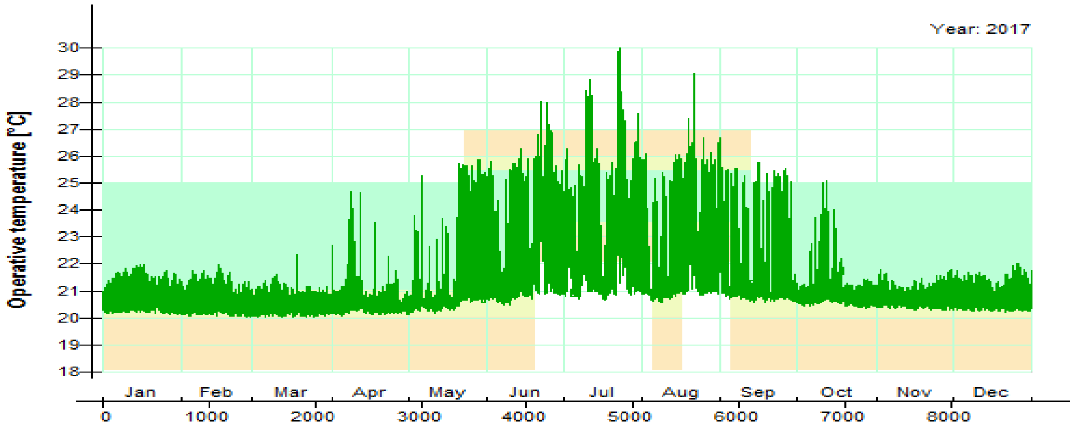
	Envelope & Thermal bridges, kWh	Window & Solar, kWh	Infiltration & Openings, kWh
Total	-11715.1	-198.1	-871.6
During heating	-11475	-206.8	-854.4
During cooling	-95.3	8.4	-8.8
Rest of time	-95.3	8.4	-8.8

Table 11 shows envelop heat transmission of the 13th-century Mongolian yurt. From the result, the heat is mostly lost through the walls and roof.

Table 13: Envelop heat transmission of the 13th-century Mongolian yurt

	Walls and roof	Floor	Doors	Thermal bridges
Total	-7807.5	-1348.7	-441.4	-2805.9
During heating	-8173.2	-855.8	-450.8	-2695.0
During cooling	378.6	-411.4	2.12	-56.5
Rest of time	-12.9	-81.5	-2.8	-54.4

In *Figure 35* illustrated the thermal comfort categories with occupancy hours of the existing yurt with the hourly resolute to the whole year.



Comfort category	No. of occupancy hours
I (best)	2014
II (good)	7771
III (Acceptable)	8029
IV (Unacceptable)	731

Figure 35: Thermal comfort distribution of operative temperatures and occupancy hours in comfort categories according to EN 15251 and ISO 7730 of the exciting yurt.

In *Figure 36* illustrated the indoor air quality, indicated the CO_2 ppm level of the existing 13th-century Mongolian yurt.

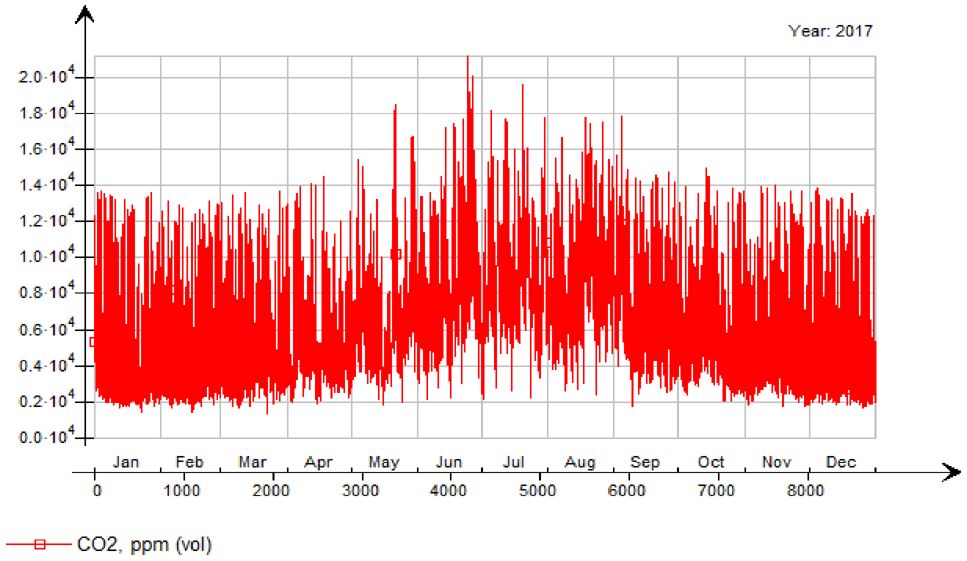


Figure 36: CO2, ppm of the exciting yurt.

4.3. Natural ventilation for the yurt

The yurt has natural ventilation, with the top opening and under the wall as called as "Dome chilling effect" (M.J.Gorman, 2005). The traditional yurt has good natural ventilation from the crown, door, and edge of the wall (khayaa). Khayaa is opened from the shaded side in summer. In this case, khayaa is simulated to be openable in the hottest 2 months in between 15th of June to 15th of August. An opening is located on the north side lower edge of the wall (*Figure 37)*. The simulation conducted without any energy for heating and cooling. The main point is to analyze how the natural ventilation of traditional yurt affects summer cooling performance.

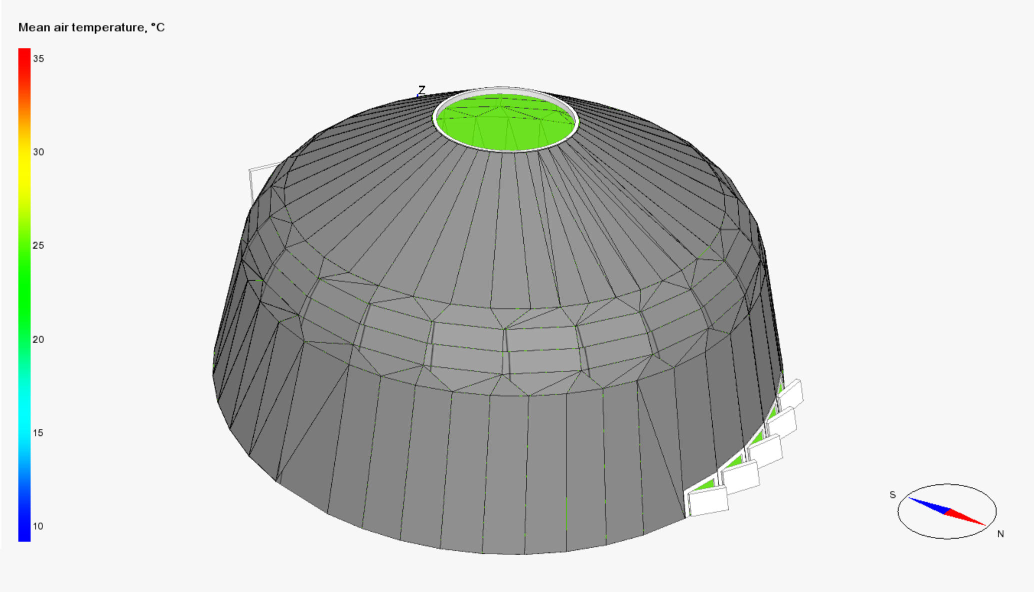


Figure 37: The yurt with the khayaa, for the natural ventilation.

Figure 35 illustrates the mean temperature of the yurt with natural ventilation. The schedule of the khayaa is set between 12:00 and 15:00 and the height of the opening are set as 300 mm. The top opening is also opened by the schedule.

The mean air temperature is decreased in the afternoon and increased during the night. The mean temperature and opening schedule have direct relationships as illustrated in *Figure 38* and *Figure 39* The mean temperature start to increase from 16:00 due to the khayaa is closed.

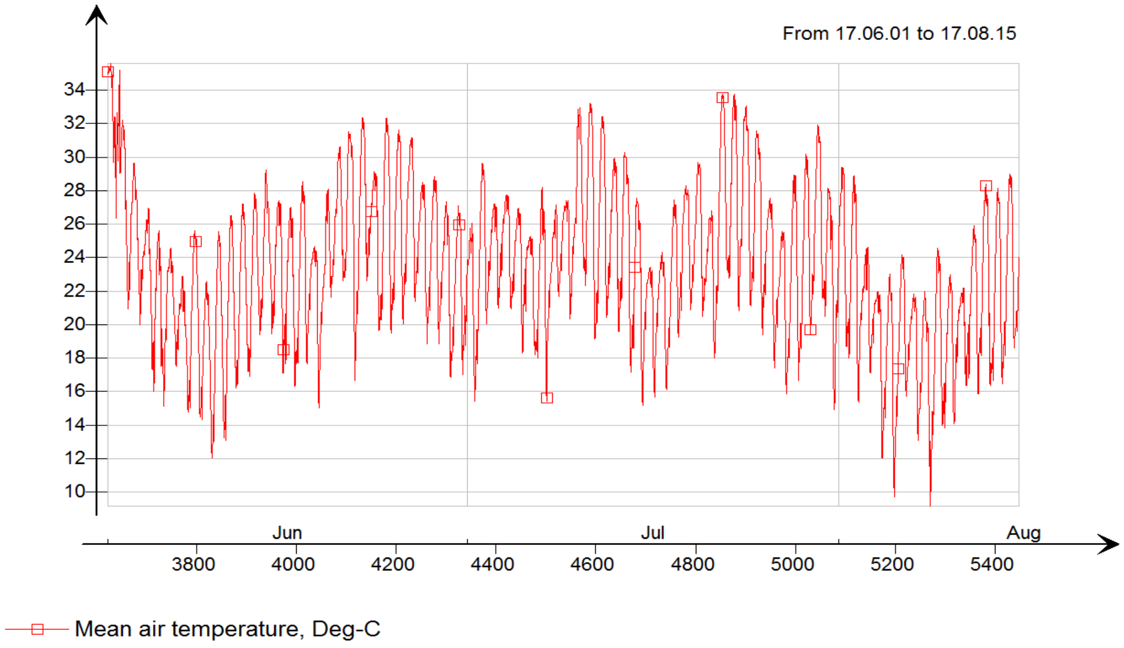


Figure 38: Mean temperature of the yurt with natural ventilation (2 months)

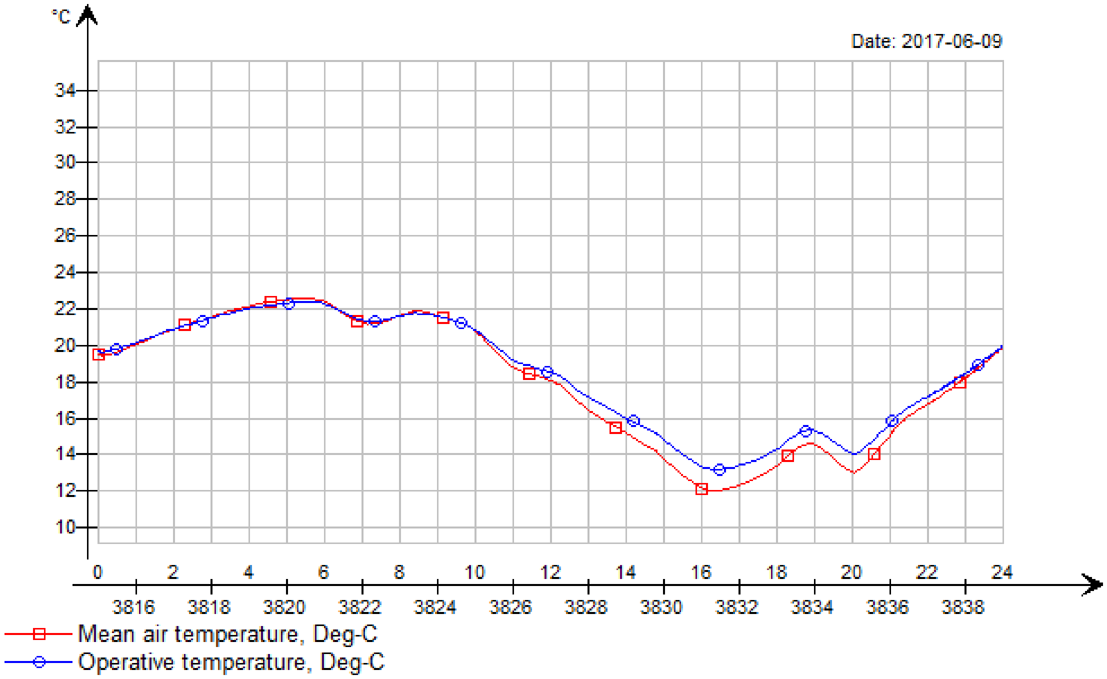
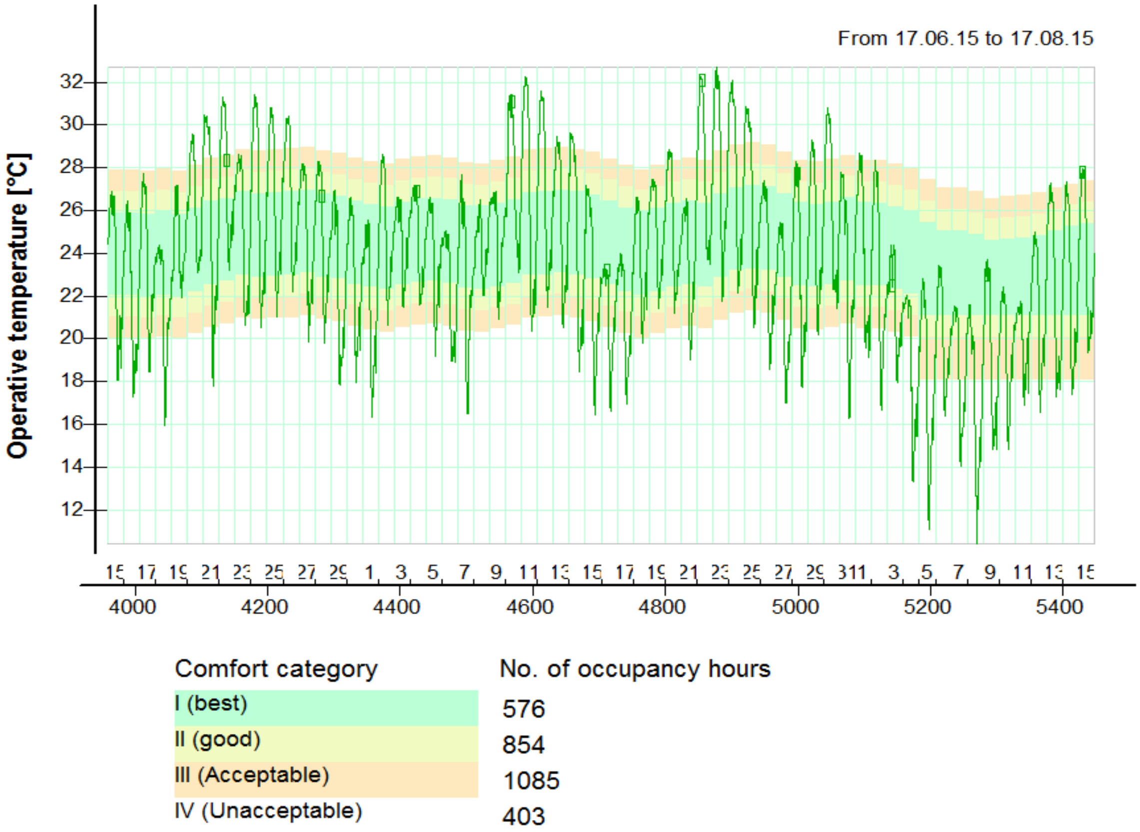


Figure 39: Mean temperature of the yurt with natural ventilation for a day.

Figure 40 illustrates the thermal comfort between June to August. The unacceptable level of thermal comfort shows overheating in the night and cooling during the day, due to the ventilation that cools down the indoor air.



Comfort category	No. of occupancy hours
I (best)	576
II (good)	854
III (Acceptable)	1085
IV (Unacceptable)	403

Figure 40: Thermal comfort of the yurt from June to August.

Figure 41 illustrates the CO_2 (ppm) of the yurt with natural ventilation. The CO_2 follows the openings: door, top opening, and khayaa. From the CO_2 diagram, the best result appears during the opening of khayaa. *Figure 41* shows the CO_2 decreased at 7 o'clock because the door is opened.

The natural ventilation highly supports cooling and ventilation of air changing mechanism of the yurt in the summertime. In winter, the natural ventilation is not practicable, because the yurt has huge heat losses from the openings. During the winter time, mechanical ventilation is suitable for ventilation.

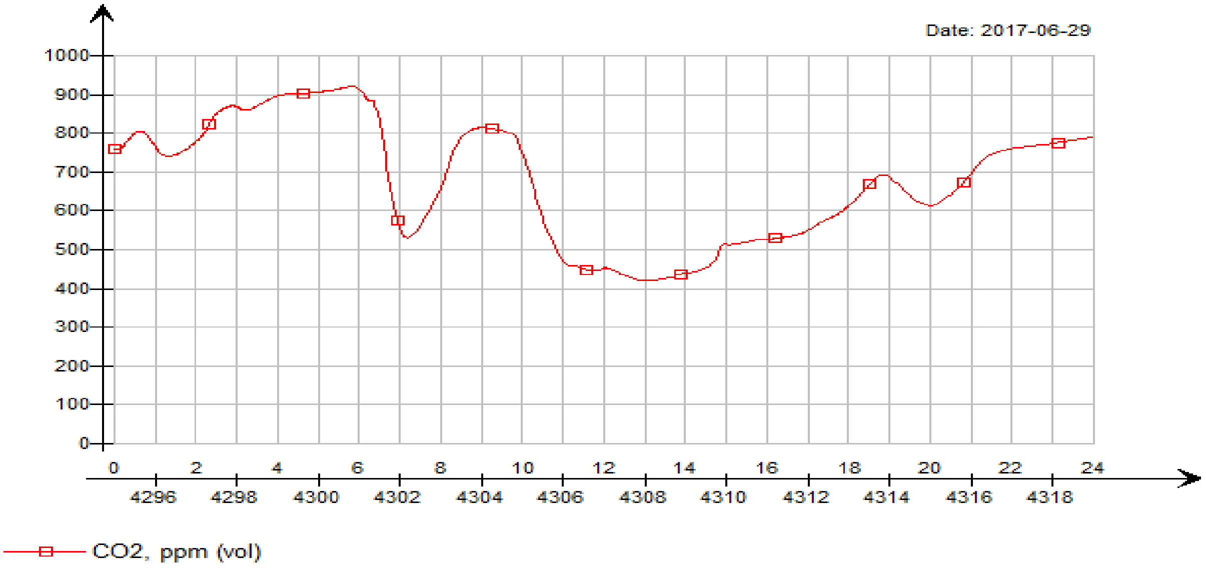


Figure 41: CO2, ppm of the yurt during natural ventilation for a day.

4.4.Conclusion

Measurement

The indoor air temperature of the yurt is much different on the different heights. Near the door temperature -4.1°C to 10.6°C, 20 cm height of north side temperature is 8.8°C to 15.8°C and near the crown temperature is 22.4°C during outdoor temperature average temperature is -33°C .

The indoor average temperature is 16.2°C which is not provided the indoor thermal comfort of the yurt. The main heat loss is through the door and khayaa.

Traditional yurt simulation

The nomadic vernacular architecture has high potential to develop into modern building requirement in terms of energy positive and high comfortable building while keeping the main functions of adaptable, lightweight and transportable. The size of the yurt can be flexible but, the shape is its main feature and it should not be changed. The size of the yurt is better to match with the purpose of using yurt.

For future developments of the yurt in terms of additional elements, it should be separable from the wooden structure. The elements and details have to portable and lightweight. The combined yurt and developed yurt investigated in this study.

Natural ventilation

Openings work very well in natural ventilation for the summer season. The top opening and khayaa (lower openings) are good combinations to ventilate the interior. In simulation results between the 15th of June and 15th of August, the mean temperature and opening schedule show interrelated results. During the daytime between the 12:00 to 15:00 the khayaa is set as opened and mean temperature has shown to be decreasing while during the closed time mean temperature was increased. The CO_2 level distribution in time is also directly related to openings. The natural ventilation provides the cooling of the yurt.

5. DEVELOPMENT OF THE MOST EFFICIENT VERNACULAR YURT VERSION

5.1.Openings (OP)

In this sub-section, at first, the different types of top openings will be examined in terms of their system energy, delivered energy, thermal comfort, heat loss and solar gain of opening, and daylighting. Then the best resulted top opening will be selected for the second step which tests different windows. As the last step, the door is insulated by new materials to be tested for heat loss.

Top opening

The top opening works as a skylight and which is the main part of the ventilation of the yurt [1], [2]. Top opening has one of the greatest heat loss elements of the yurt, reaching 10.7% to 50.9% heat loss from the simulation result of traditional yurts' examination. In below *Figure 42,* three different types of yurts are illustrated. However, there are 5 different types of top openings in relation to the differences in glazing.

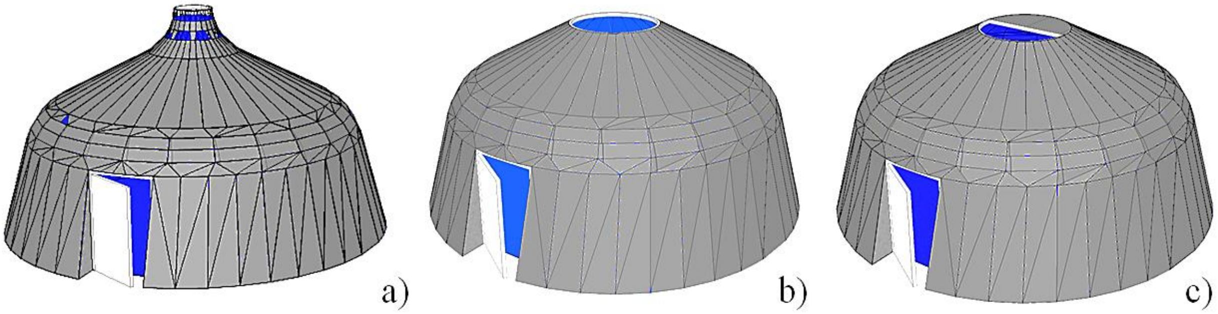


Figure 42: Different types of yurt top opening, a) OP-01, OP-02, b) OP-03, OP-05, c) OP-4.

In the upcoming discussions, 'a' type of yurt involves to the top opening (OP)-01; OP-02; 'b' involves to OP-03 and OP-05, and 'c' involves to OP-4. In below *Table 12*, the detailed information on top openings has illustrated in terms of systemized opening types, diameter, area, and glazing types (*Figure 42*).

Table 14: Detailed information about the top opening for the yurt.

Opening type	Diameter, m	Area, m²	glazing type
OP-01	0.591	0.27	3 pane glazing
OP-02	0.591	0.27	1 pane glazing
OP-03	1.398	1.53	3 pane glazing
OP-04	1.398	0.82	3 pane glazing
OP-05	1.398	1.53	1 pane glazing

The OP-3 is best resulted, during the heating (*Figure 44*) and OP-02 is best resulted for a cooling period (*Figure 43).*

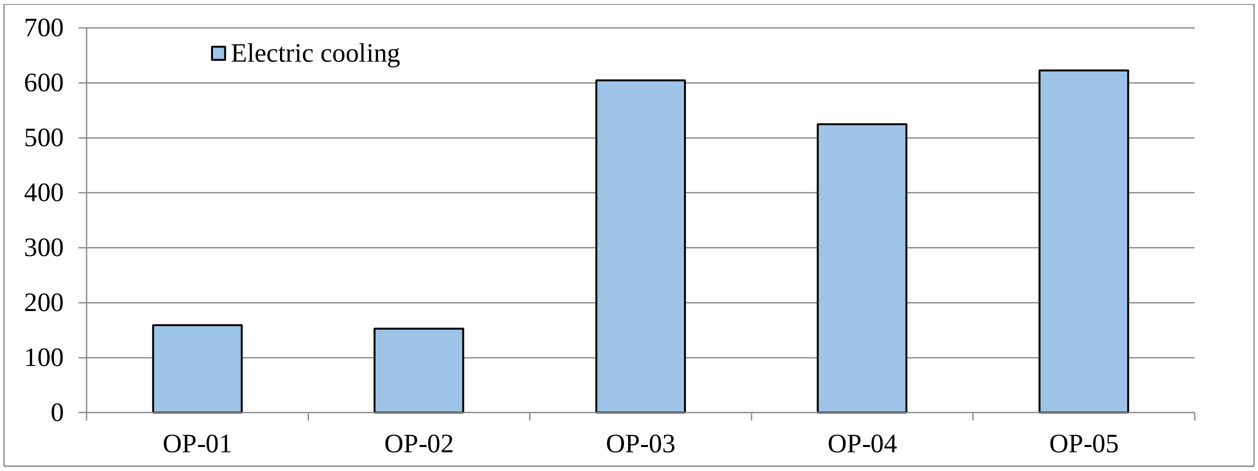


Figure 43: Cooling in delivered energy of different top openings

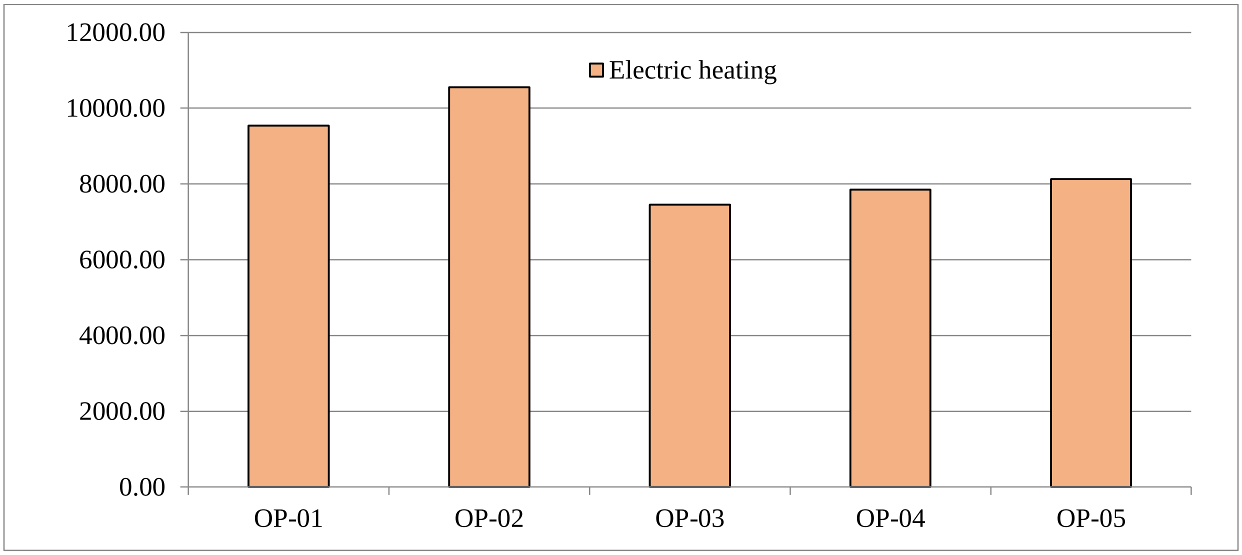


Figure 44: Heating in delivered energy of different top opening.

Heat loss and gain

In below *Figure 45*, the heat loss and heat gain of the yurt top openings are illustrated. The best type of top opening is OP-1 as it shows the lowest result in heat loss and heat gain.

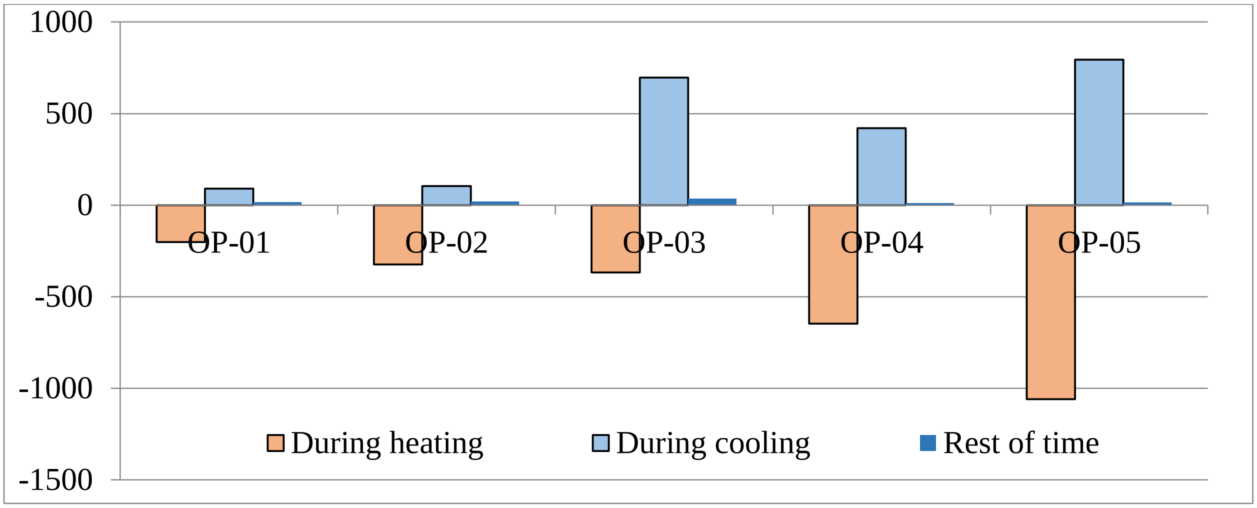


Figure 45: Heat loss and heat gain of the top opening for the yurt.

Thermal comfort

All types of top opening with glazing show the same results in terms of thermal comfort with occupancy hour setting as illustrated in below *Figure 46*.

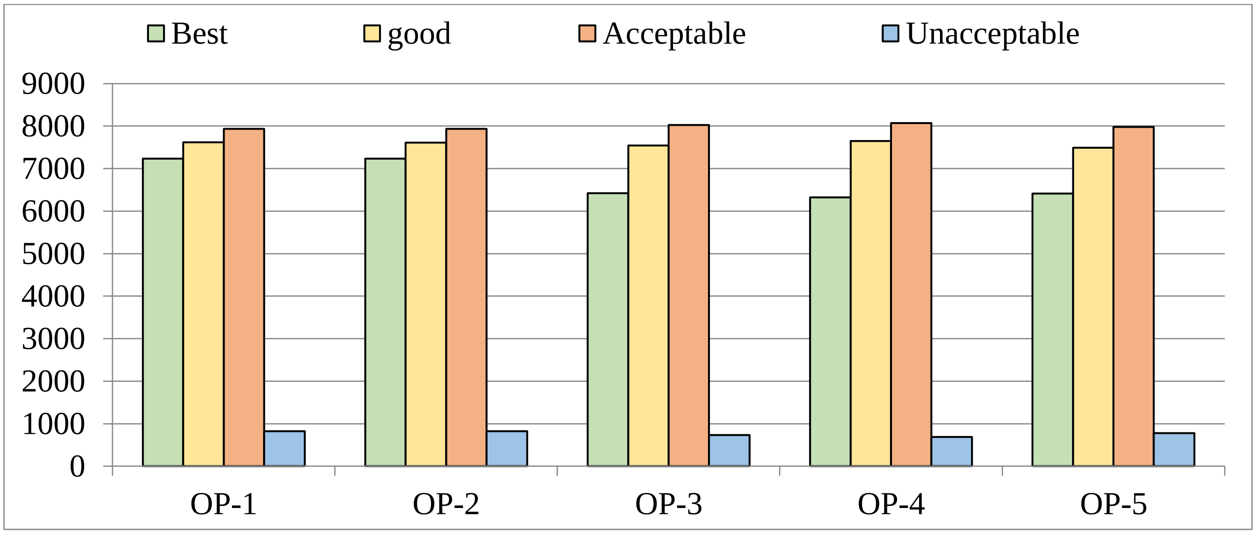


Figure 46: Thermal comfort comparison for the top opening of the yurt with numbers of occupancy hours.

Daylight

For the daylight factor, only two types of top opening have considered for further examination as the 5 top-openings have 2 different glazing variations. Below *Figure 47,48* illustrates the daylighting of the two top-openings: 1) the small top opening (see *Figure 42- a*) and 2) bigger top opening (see *Figure 42 - b*). The small top opening daylighting result shows less than 1000 Lux (*Figure 47*) and the bigger top opening daylighting result shows between 0 and 10000 Lux in *Figure 48*.

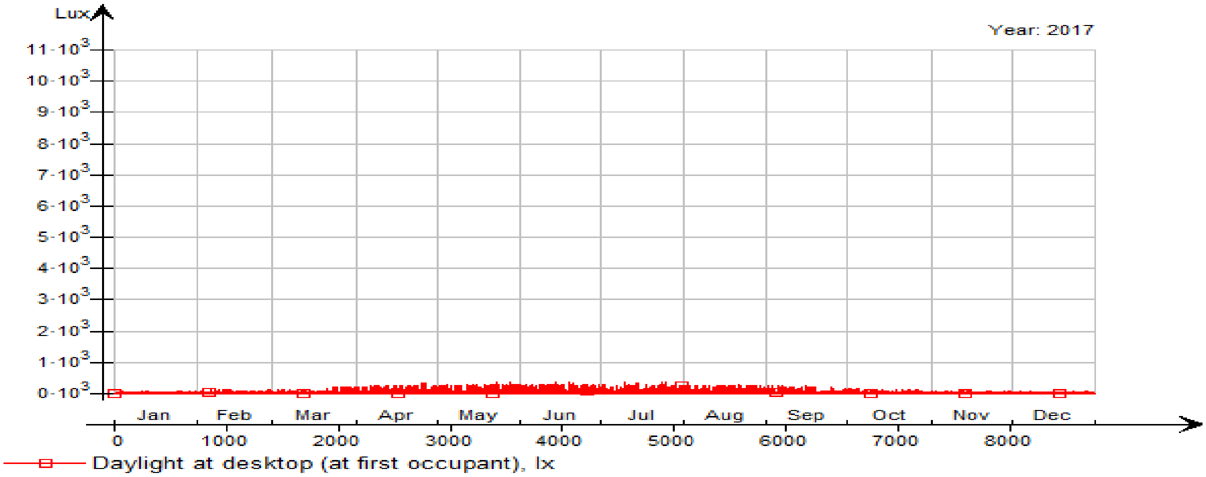


Figure 47: Daylighting at the desktop of OP-2 (8760 h)

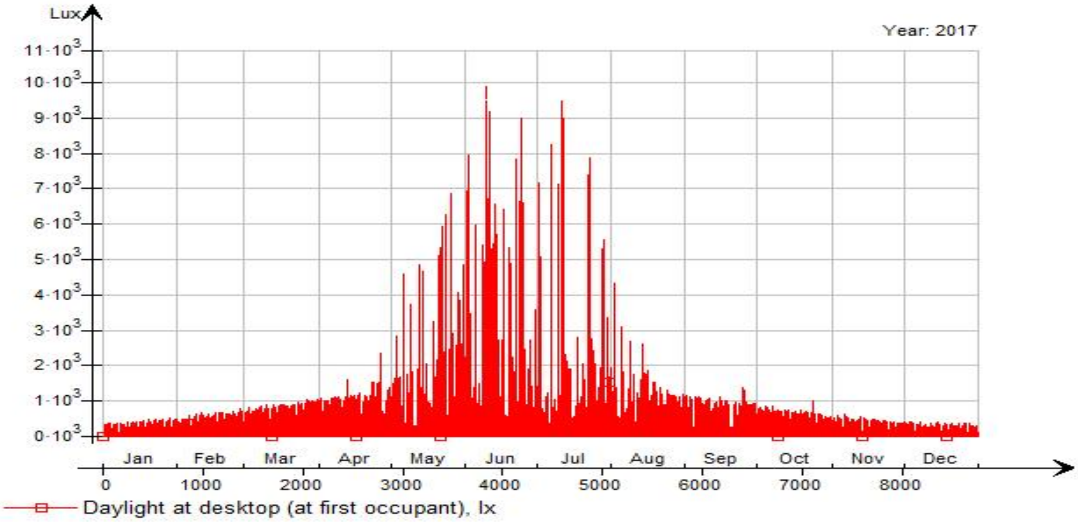


Figure 48: Daylighting at the desktop of OP-5 (8760 h)

Window

The best glazing percentage depends on the transmission heat loss, solar gains in winter and the solar input in summer [26]. The glazing percentage of the north, east and west facade is 30% to 40%, and the south facade glazing percentage is up to 50% (Hausladen, 2012). For the window development, OP-3 opening type has selected as a base for window development as which has shown the best result in thermal analyses. 6 different types of windows are designed for simulations, which are numbered as OP-6 to OP-11 as illustrated in below *Figure 49.*

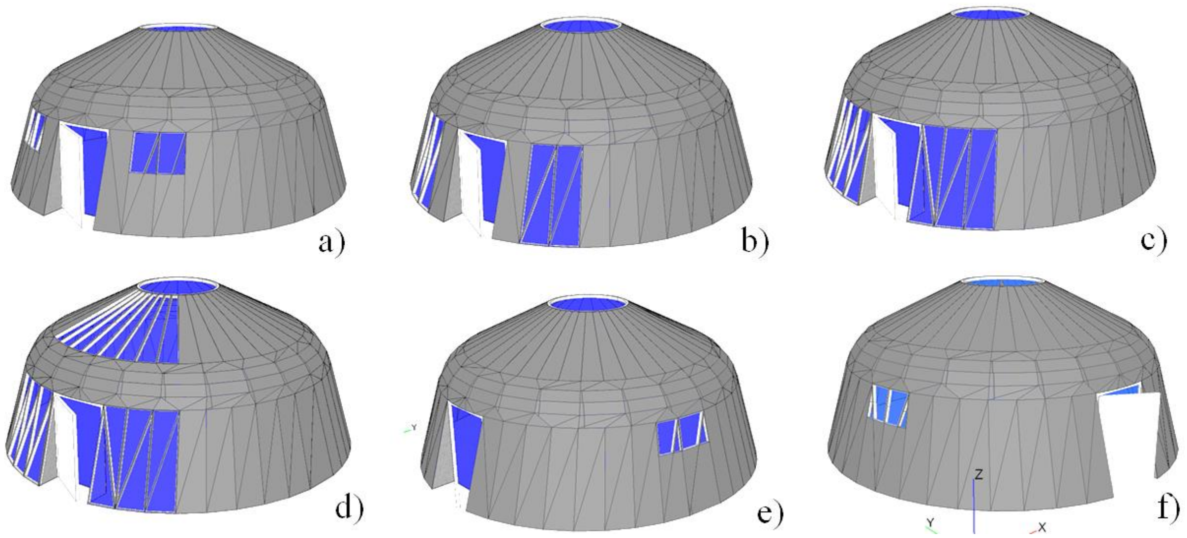


Figure 49: Window types of the yurt, a) OP-06, b) OP-07, c) OP-08, d) OP-09, e) OP-10, f) OP-11.

In *Table 13* elevation sides, area, and glazing types of the window are shown with respect to each systemized opening types.

Table 15: Types of the window for the yurt

Opening type	Elevation side	Area, m^2	glazing type
OP-06	South	0.92	3 pane glazing
OP-07	South	2.44	3 pane glazing
OP-08	South	3.66	3 pane glazing
OP-09	South	6.7	3 pane glazing
OP-10	East	0.48	3 pane glazing
OP-11	West	0.4	3 pane glazing

The results from delivered energy on the different types of windows are illustrated in *Figure 50* and *51*.

Type of OP-07 best results in the heating in delivered energy illustrated in *Figure 50*.

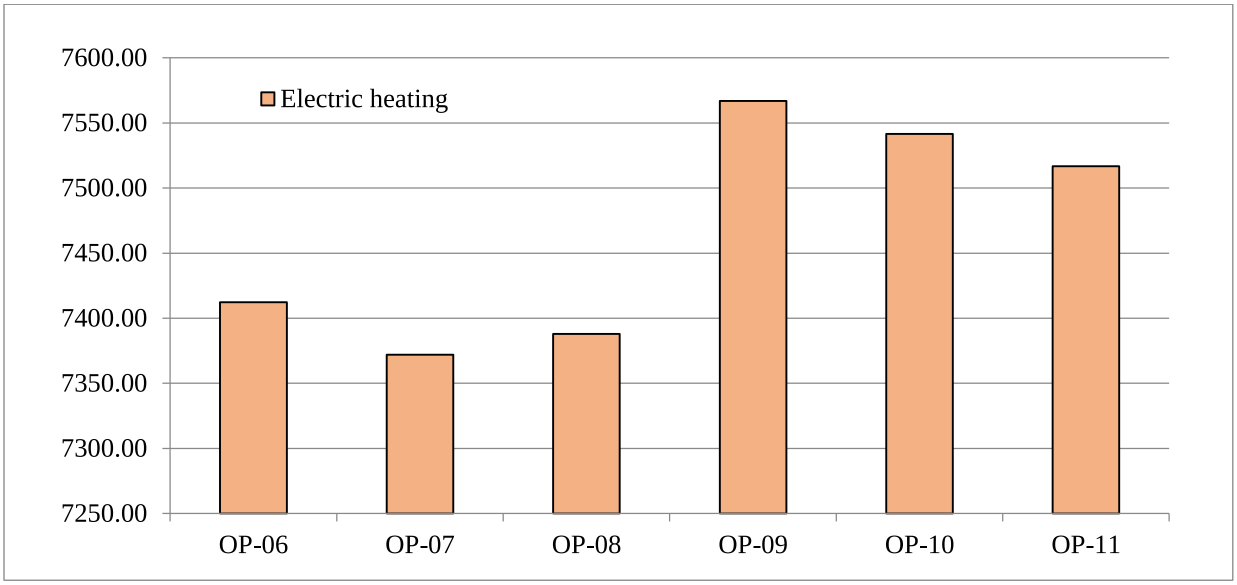


Figure 50: Heating in the delivered energy for the different windows of the yurt

In Figure 51illusterated the cooling energy for the different windows of the yurt, the best-resulted window type is OP-10 and Op-11.

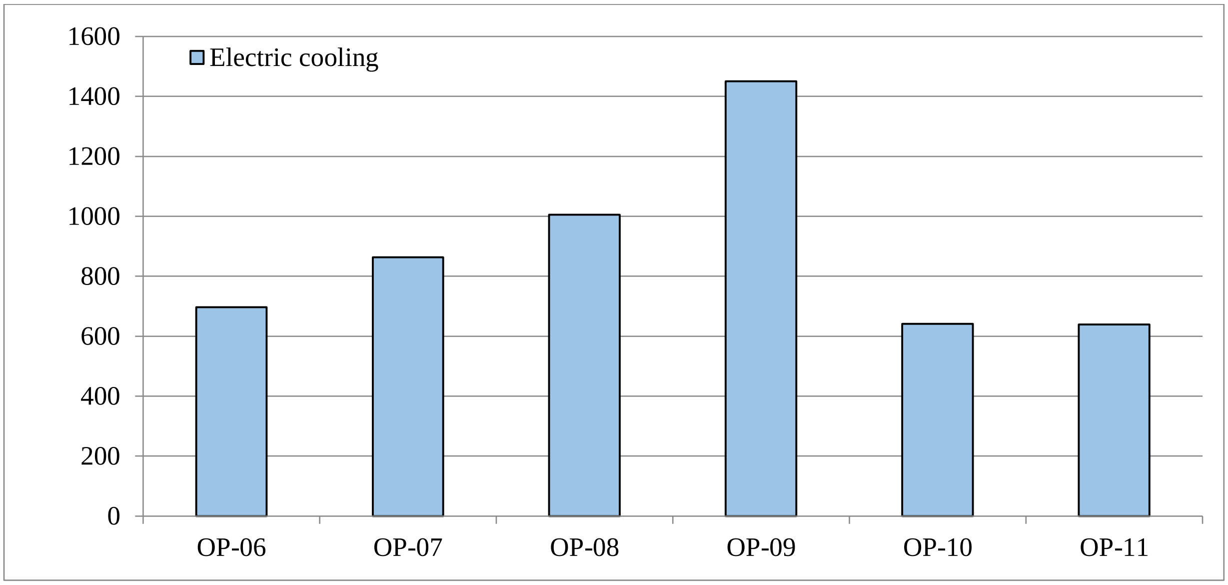


Figure 51: Cooling in the delivered energy for the different windows of the yurt

During the heating, OP-06; 07; 08 shows little support for heating compared to OP-03. During the cooling, heat is gained through windows OP-06; 07; 08. Window area and energy balance are directly related (*Figure 52*).

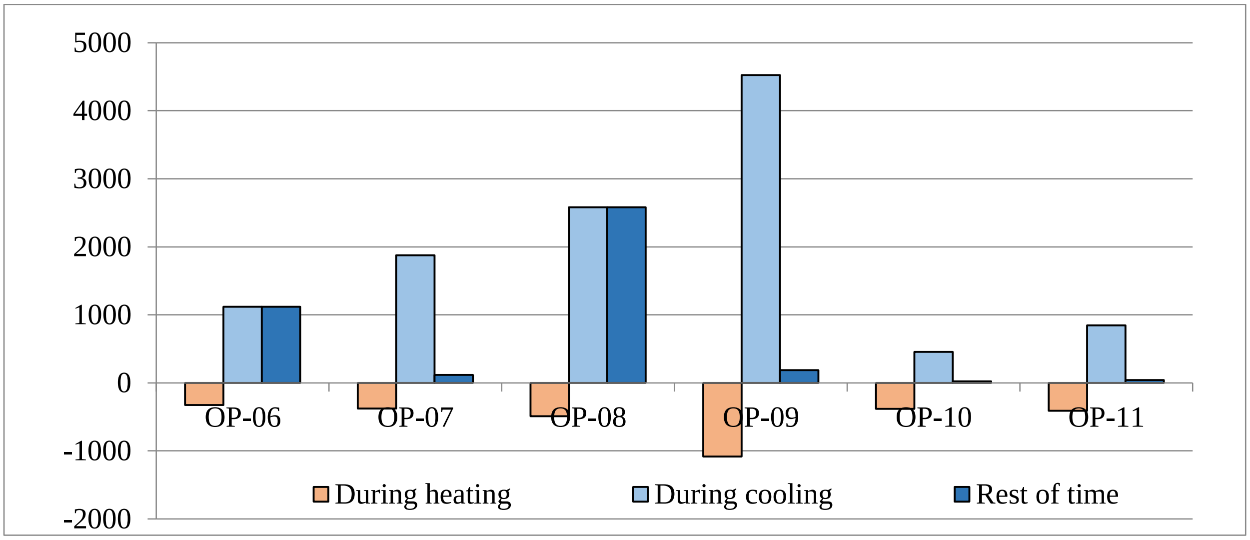


Figure 52: Heat loss and heat gain through the window and solar (kWh)

Thermal comfort

Comparison of thermal comfort for the 6 types of windows is illustrated in below *Figure 53*. OP-07 shows the best result and the OP-9 shows the least.

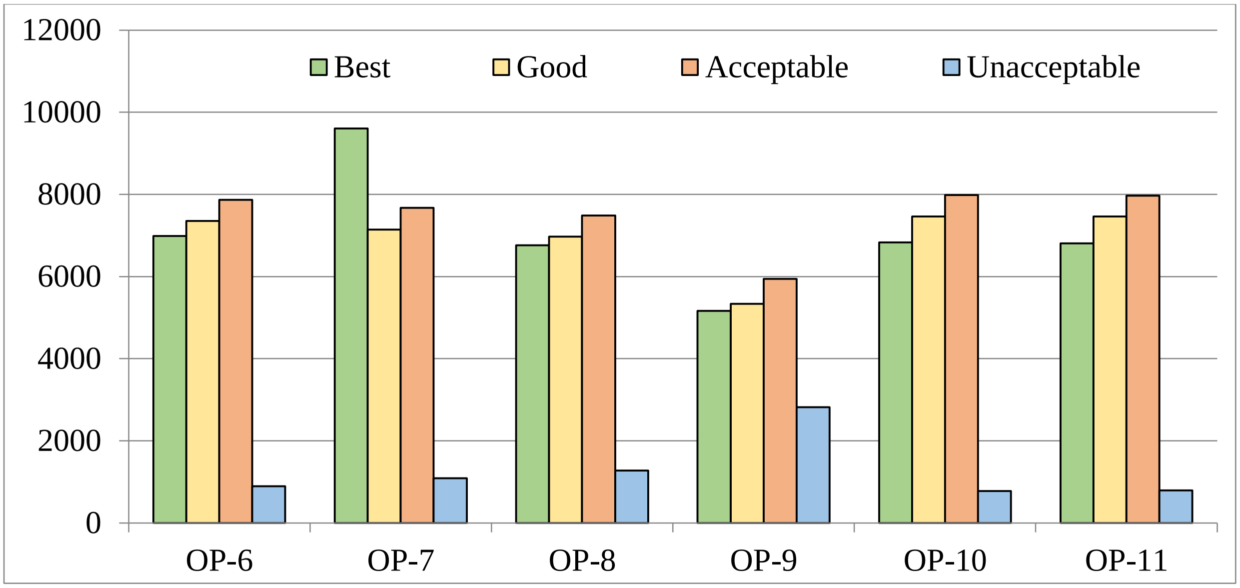


Figure 53: Thermal comfort comparison for the window of the yurt with numbers of occupancy hours.

Door

The door is in many ways similar to windows but the door can be made by the solid material [31]. The insulated door has lesser heat loss than a solid door [31]. The existing yurt has a wooden solid door which is 40mm thick and its U-value is 2.194 W/m^{2}K. The door has 441.4 kWh heat losses in the energy balance from the thermal simulation results.

To improve the door insulation, 12 mm thickness of Silica aerogel blanket insulation material was tested and which reduces the U-value almost three times less than the existing wooden door, which is 0.7437 W/(m^{2}K). From the thermal dynamic simulation result, the door heat loss is potential to be decreased to 153.8 kWh after the new insulation.

5.2. Orientation

Orientation supports heating in winter season through solar gain but increases the cooling requirement during summer [31]. Also depending on the air pressures received from different wind directions, orientation effects on building airflow [31]. For orientation optimization, computer simulations enable the best calculation as it is fairly quick and most programs allow rotating the building [31]. The traditional yurt is usually oriented to the south, in exceptional or special circumstance different orientation is chosen (Banzragch, 2006) (Bat-Ulzii.B, 2016).

Simulation result for the orientation

The orientation compression of the yurt system energy is calculated using thermal dynamic simulation. The results are shown in below 18 *Figure 54*. In the system energy setting, no significant difference was found except the little bit higher results shown in the south and south-east orientation.

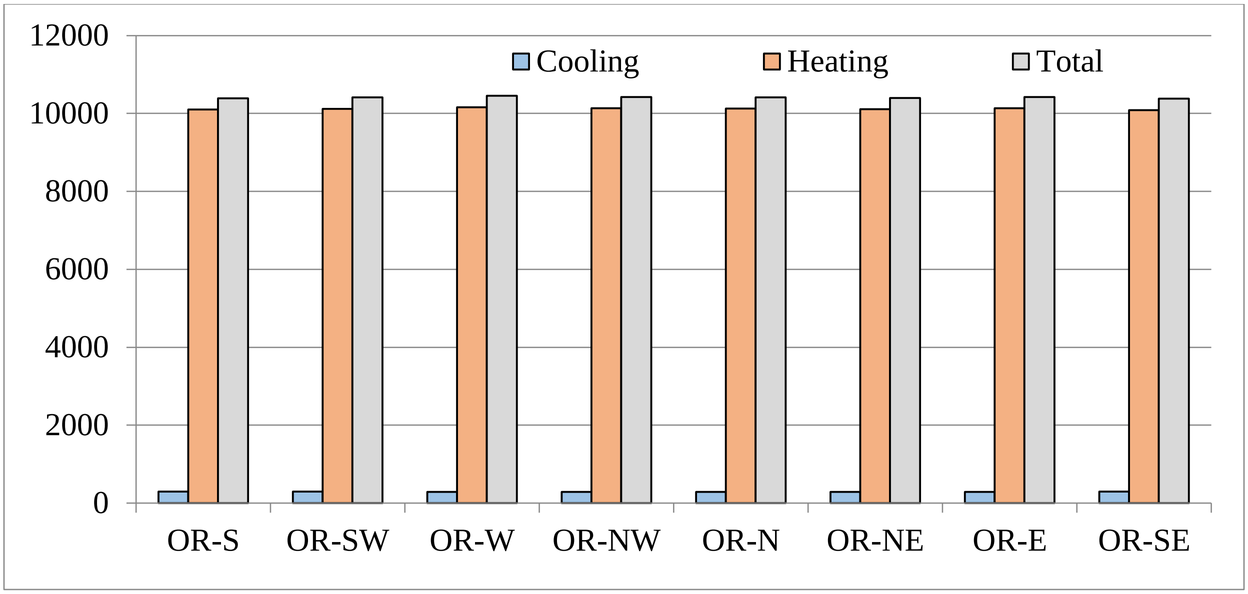


Figure 54: Orientation compression of the system energy

Figure 55 illustrates the comparison of delivered energy with different orientations for the yurt. The result has not a big difference between each model with different orientation.

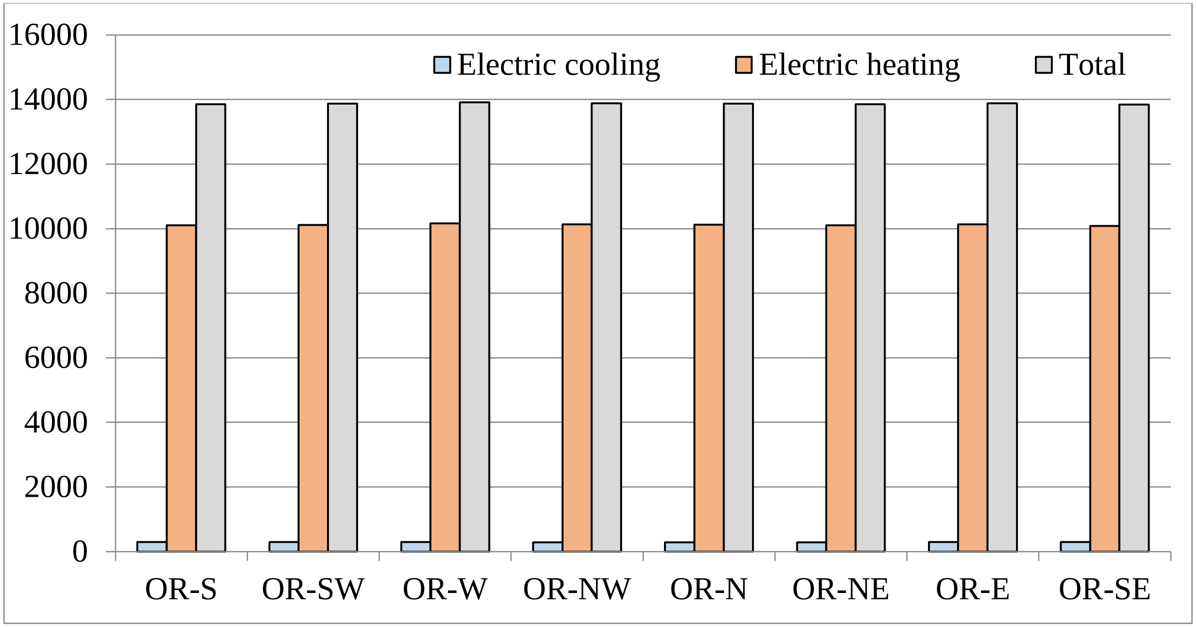


Figure 55: Orientation compression of the Delivered energy for the yurt.

The results on thermal comfort comparative graphics of the different orientations are illustrated in Figure 56. The results for orientations show the same findings which indicate that orientation does not effect yurt thermal comfort.

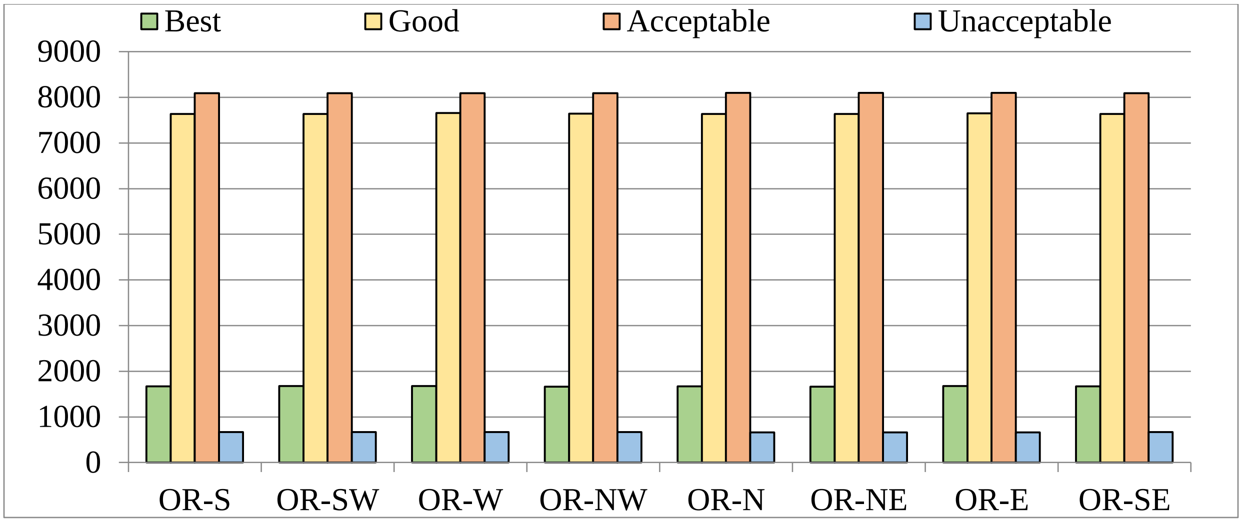


Figure 56: Comparative assessment of the thermal comfort for the different orientations.

No effect in yurt orientation is also related to the yurt shape and only one window is located on the top where the only potential difference is the door location.

5.3. Structures, materials

Simulation results for comparison of different materials, SM-01to SM-08

The materials which are currently used and potential to be used are systemized in *Table 14* in terms of their material density and thermal conductivity and the information is used for simulation. The materials potential to be used for yurts are selected on the basis of the characteristics of lite weight, flexible, and durable to the nomadic building.

Table 16: Materials, material density, material thermal conductivity (standard, 2007) (Ariunbold.L, 2009) (Frydrych, 2009) (Domínguez-Muñoz, 2010) (Abdou, 2013) (Bardy Erik .R, 2007) (Coffman.B.E, 2010) (Simmler, 2005) (Milena, 2006).

materials	density, [kg/m3]	thermal conductivity, [W/(mK)]	Specific heat, [J/kgK]
Sheep wool felt	70	0.04	1700
Rockwool	45-75	0.039	840
Glass wool	30	0.032	840
Mineral wool	145	0.0358	840
Sheep wool insulation	30	0.039	1700
Silica aero gel blanket	120	0.0135	1700
VIP	200	0.004	1600
PCM	900	0.5	2500
Membrane	302.2	0.0662	1900
Tarpaulin	250	0.09	1960
Cortex	646.57	0.04332	1800

The various materials for wall and roof are tested for thickness; U-value of yurt and U-value of the wall and roof are illustrated in *Table 15*. Material selection for yurt is crucial, as significant heat is lost through the envelope. Insulation materials (traditional sheep wool felt, basalt wool, glass wool, silica aerogel blanket, and vacuum insulated panel-VIP) are compared using thermal dynamic simulations while setting the same thickness for all materials (*Table 15*). The U- the value of the yurt and the U-value of the yurt's wall and roof are calculated by the thermal dynamic simulation tool IDA-ICE 4.8, based on the material density, specific heat, and thermal conductivity.

Table 17: Types of the yurt, materials, thickness, U- value of the yurt and u-value of wall and roof, (SM-Structural material).

Type of the yurt	Materials	material thick [mm]	U-value of the yurt, [W/(m2K)]	Wall and roof U-value [W/(m2K)]
SM-01	Sheep wool felt	60mm	0.6519	0.5988
SM-02	Tarpaulin, sheep wool felt.	2mm, 60mm	0.6466	0.5545
SM-03	Tarpaulin, basalt wool	2mm, 60mm	0.6383	0.5778
SM-04	Tarpaulin, glass wool	2mm, 60mm	0.5784	0.4837
SM-05	Tarpaulin, mineral wool	2mm, 60mm	0.6112	0.5353
SM-06	Tarpaulin, sheep wool insulation	2mm, 60mm	0.6383	0.5778
SM-07	Tarpaulin, Silica aerogel blanket	2mm, 60mm	0.4075	0.2157
SM-08	Tarpaulin, VIP	2mm, 60mm	0.312	0.06582

Figure 57 illustrates a comparison of cooling in the system energy for the yurt with different insulation materials. The simulation result shows, SM- 07 and SM-08 (Structural material) are the best materials for the cooling.

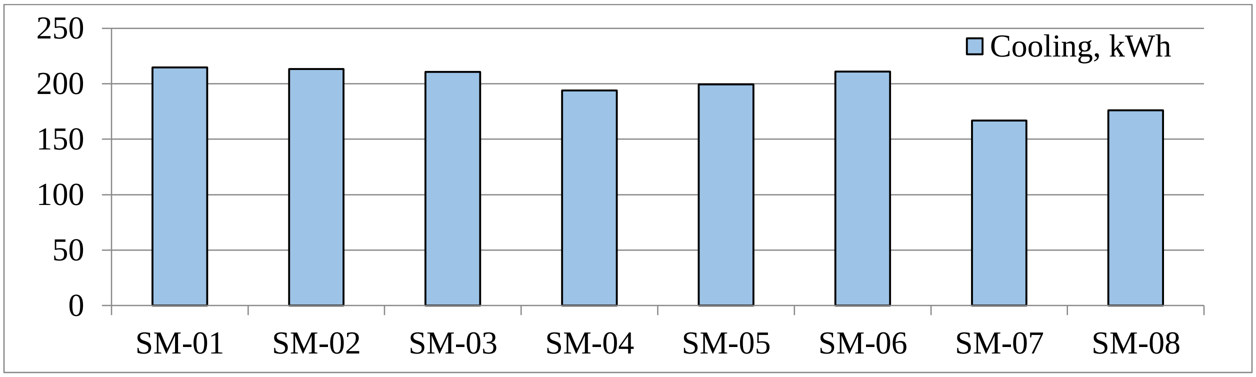


Figure 57: Used cooling demand in system energy of different materials for the yurt (kWh).

Figure 58 illustrated materials comparison heating in the system energy for the yurt. The heating SM- 01 to SM- 06 (Structural material) did not show a big difference for the heating in the system energy. SM-07 and SM-08 provided the best result in the simulation result.

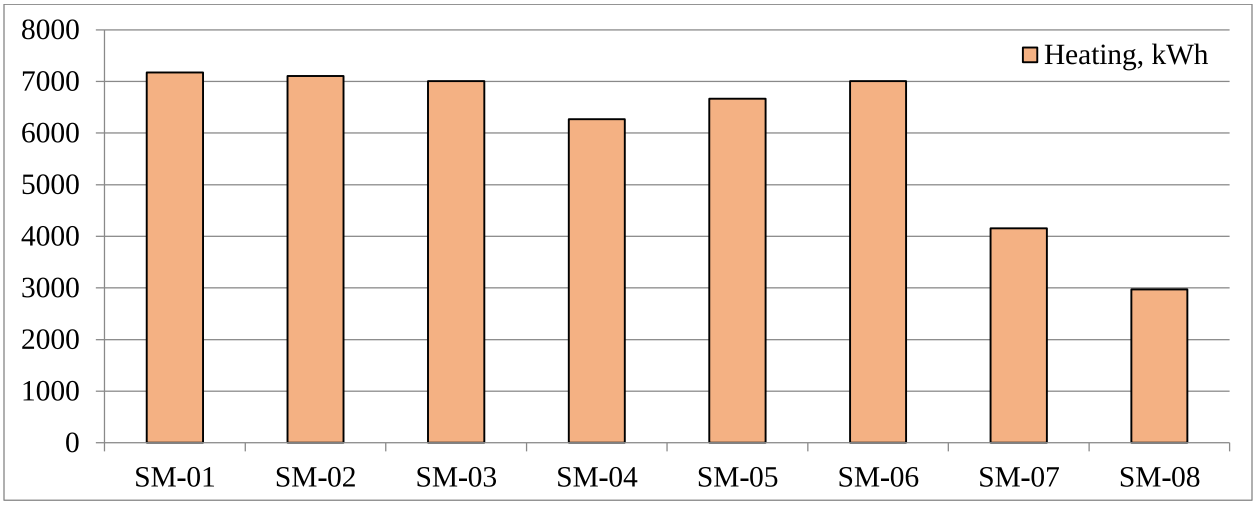


Figure 58: Used heating demand in system energy of different materials for the yurt (kWh)

Figure 59 shows the thermal dynamic simulation result on the delivered energy of different materials.

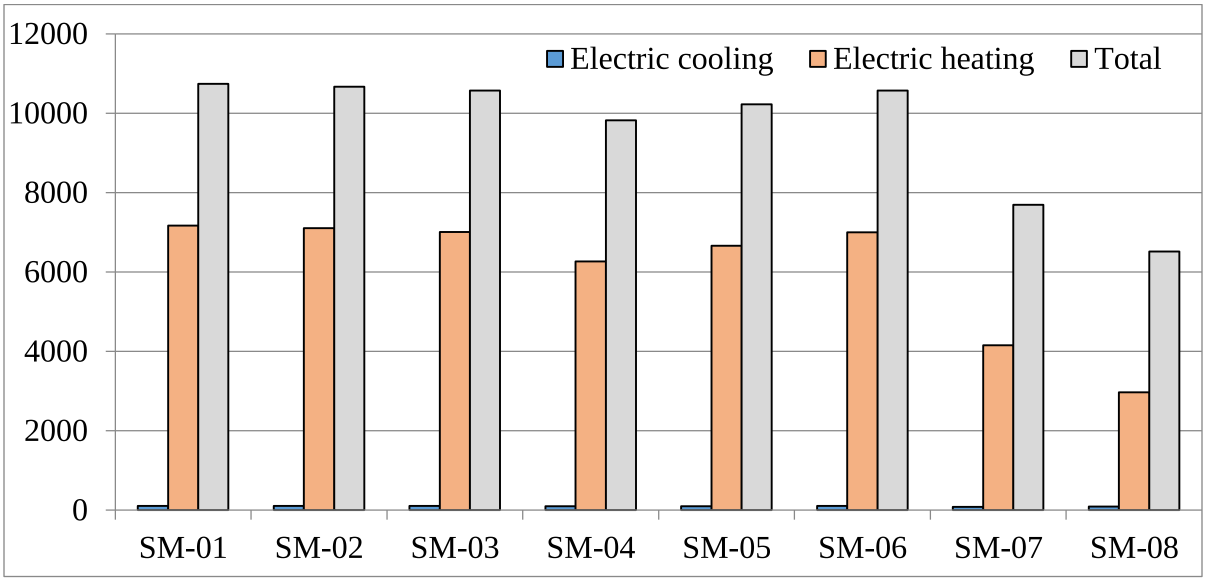


Figure 59: Delivered energy of the yurt with different material.

Figure 60 shows the energy balance of yurts with different materials. The most heat is lost from the envelope and thermal bridges.

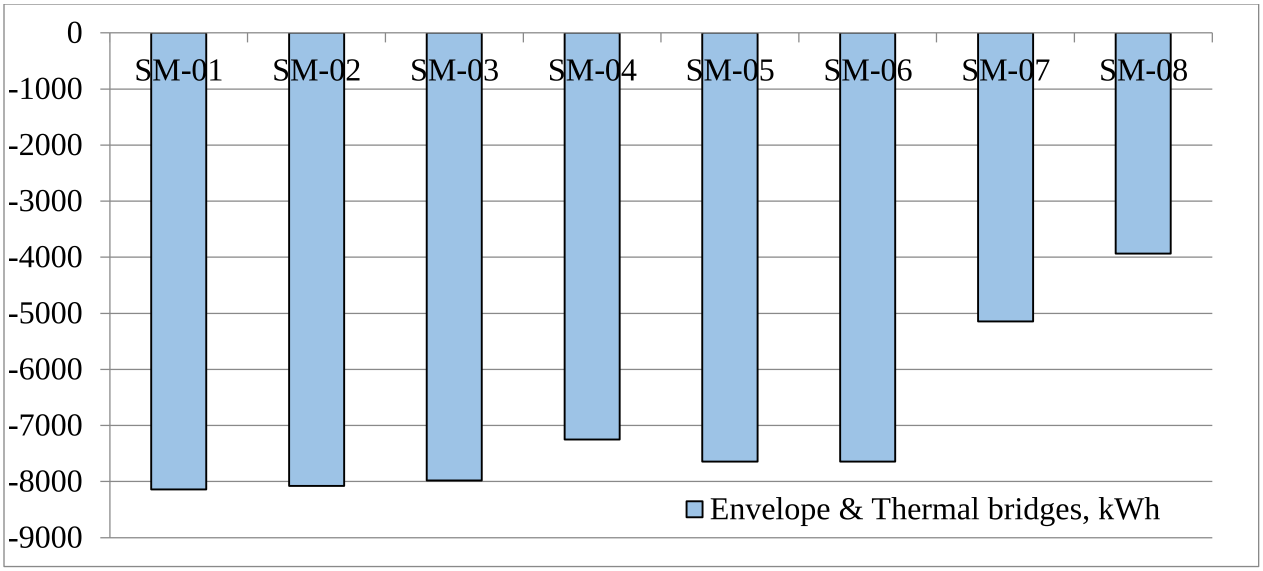


Figure 60: Energy balance of different materials for the yurt

Figure 61 shows the detailed information on heat loss arising from the enveloped area and thermal bridge in the energy balance of the yurt while applying different materials. The floor materials are set as same for all yurts. The result shows SM-07, and 08 have the lowest heat loss from the wall and roof as the insulation materials have shown the best result for thermal conductivity.

Figure 61: Heat loss from the details of a yurt in heat balance

Thermal comfort of different materials is categorized into best, good, acceptable and unacceptable levels as illustrated in *Figure 62*. SM-08 shows no unacceptable category in thermal comfort and SM-07 shows only 12 hours of the unacceptable thermal comfort.

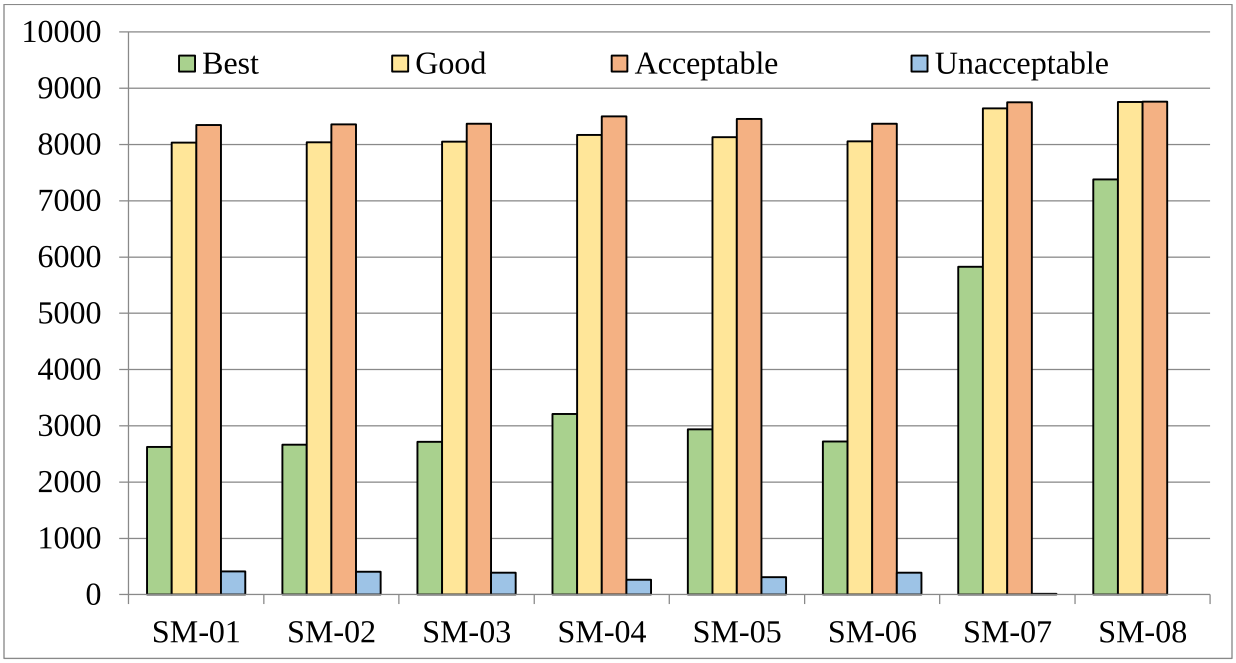


Figure 62: Thermal comfort of the different materials for the yurt with numbers of occupancy hours.

From the materials insulation comparison, VIP and Silica aerogel blanket shows the best results. However, Silica aerogel blanket is suitable for yurt due to flexible and lightweight

<u>Development of the structural material, SM-09 to SM-14</u>

For further development, Silica aerogel blanket material has chosen as it has shown the best result from the comparison simulation. Also, the material is flexible and its thermal conductivity is low (0,0135 W/(m K)). With regards to the yurt structure which is collapsible and transportable, the chosen materials must be thin and lightweight. In this case study, the maximum thickness for the insulation material is set as 100 mm insulation, 40 mm PCM (Phase Change Material) and coverage material (*Table 16*).

Table 16 shows the systemization of materials, material thickness, U–value of the yurt and U-value of wall and roof for the different materials.

Table 18: Types of the yurt, materials, thickness, U- value of the yurt and u-value of wall and roof, (SM-Structural material), SM-09 to SM-14

Type of the yurt	Materials	material thick [mm]	U-value of the yurt, [W/(m2K)]	Wall and roof U-value [W/(m2K)]
SM-09	Tarpaulin, Silica aerogel blanket	2mm, 80mm	0.3742	0.1634
SM-10	Tarpaulin, Silica aerogel blanket	2mm, 100mm	0.354	0.1316
SM-11	Tarpaulin, Silica aerogel blanket, PCM	2mm, 80mm,40mm	0.3729	0.1613
SM-12	Tarpaulin, Silica aerogel blanket, PCM	2mm, 80mm,80mm	0.3716	0.1593
SM-13	Tarpaulin, Silica aerogel blanket, PCM	2mm, 60mm,60mm	0.404	0.2102
SM-14	Tarpaulin, Silica aerogel blanket, PCM	2mm, 100mm,40mm	0.3531	0.1302

Figure 63 illustrates the used cooling demand in the system energy of different material applications for the yurt. For cooling, PCM shows the effect on SM-12 and SM-13.

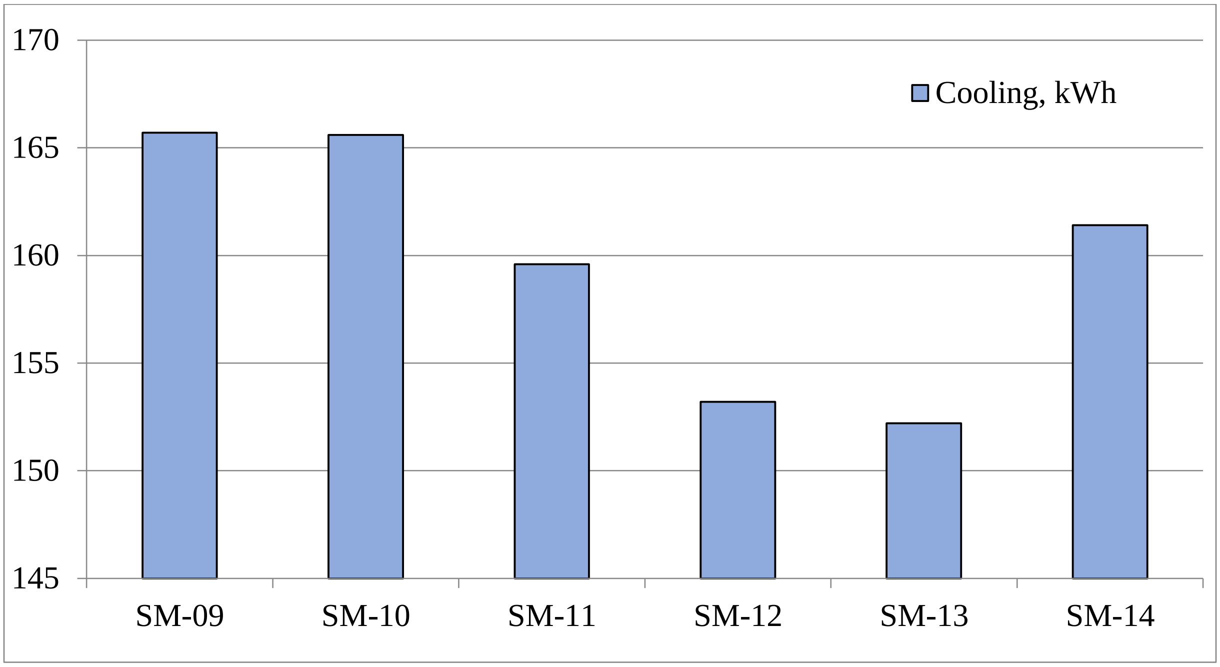


Figure 63: Used cooling demand in system energy of different materials for the yurt (kWh), SM-09 to SM-14.

The insulation material thickness is directly related to the heating. *Figure 64* illustrates the used heating energy demand in the system energy of different materials for the yurt. The SM-10 and SM-14 are the best results because the insulation material is 100 mm Silica aerogel blanket.

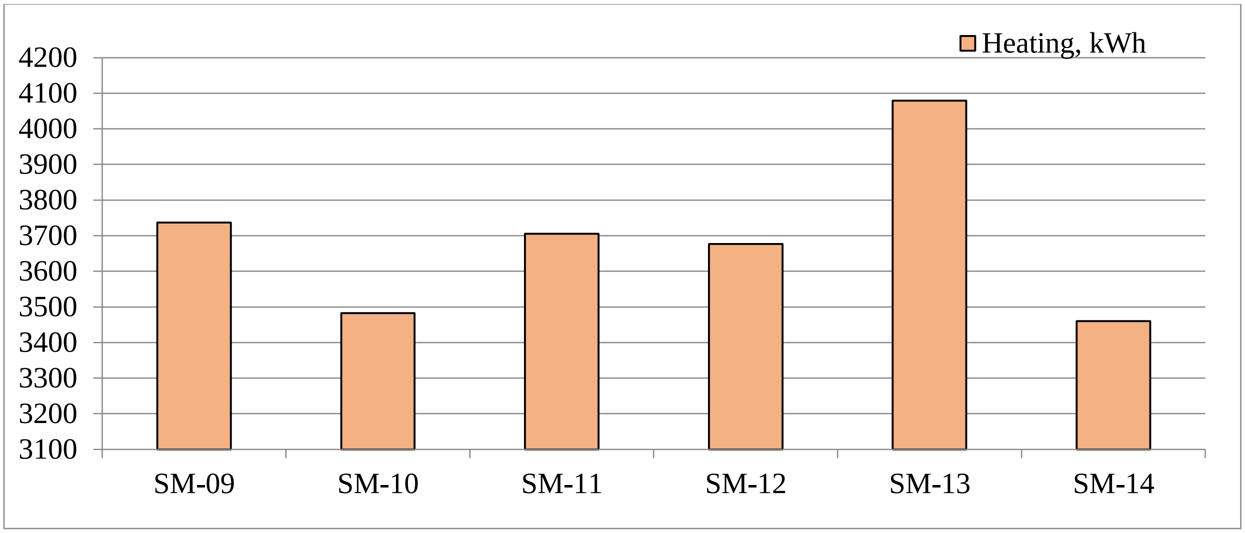


Figure 64: Used heating demand in system energy of different materials for the yurt (kWh), SM-09 to SM-14.

Figure 65 shows delivered the energy of different materials (SM-09 to SM-14) and the best outcomes are highlighted in grey.

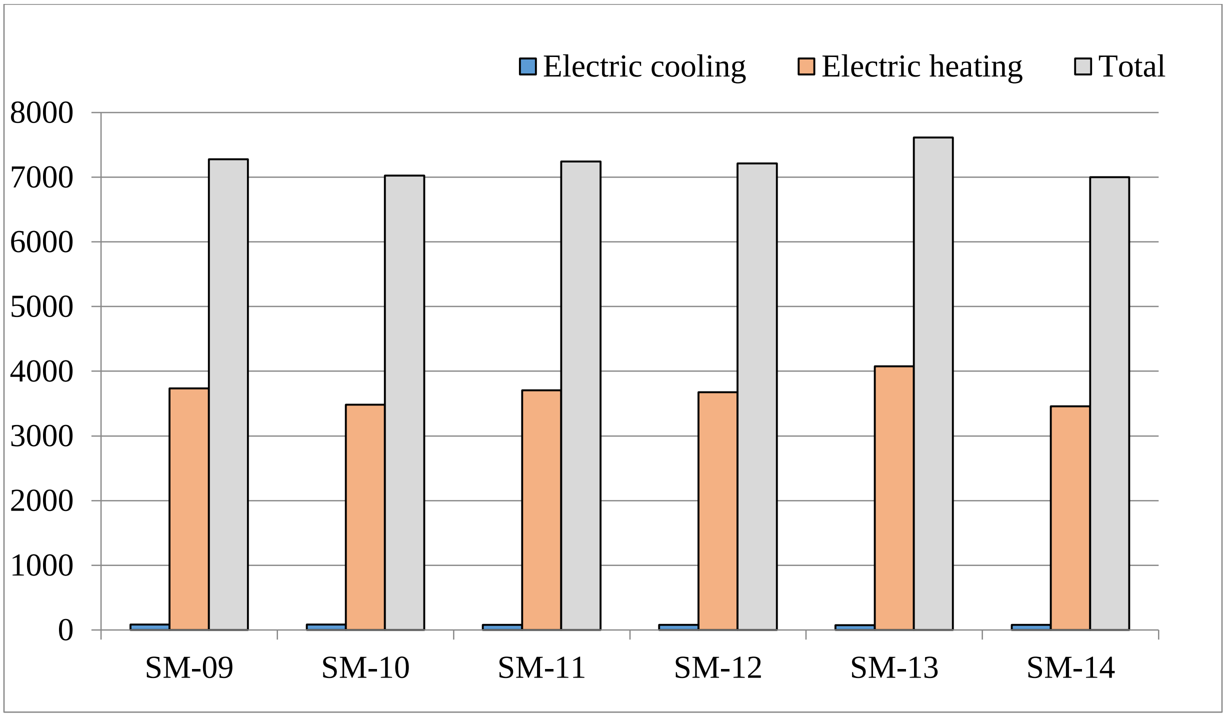


Figure 65: Delivered energy of the yurt with the different material, SM-09 to SM-14

Figure 66 shows Heat loss through the envelope and thermal bridge of the yurt with different insulation material.

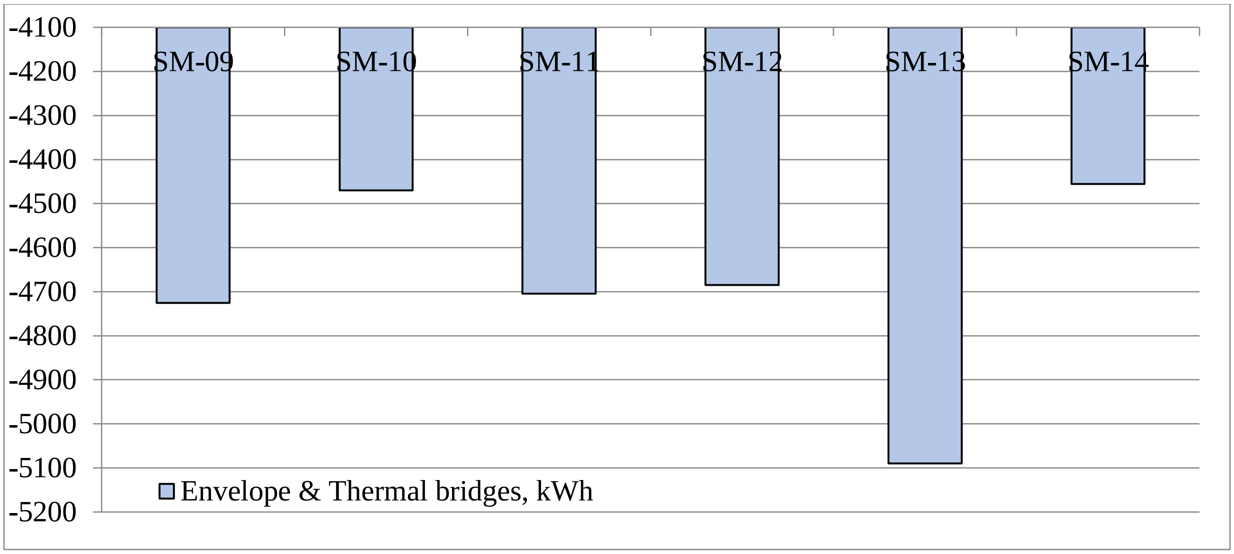


Figure 66: Heat loss through the envelope and thermal bridge of the yurt with different insulation material.

In *Figure 67* illustrated the total heat loss from the envelope area and thermal bridges of the heat balance. Walls and roof heat loss are different because the material thickness is different.

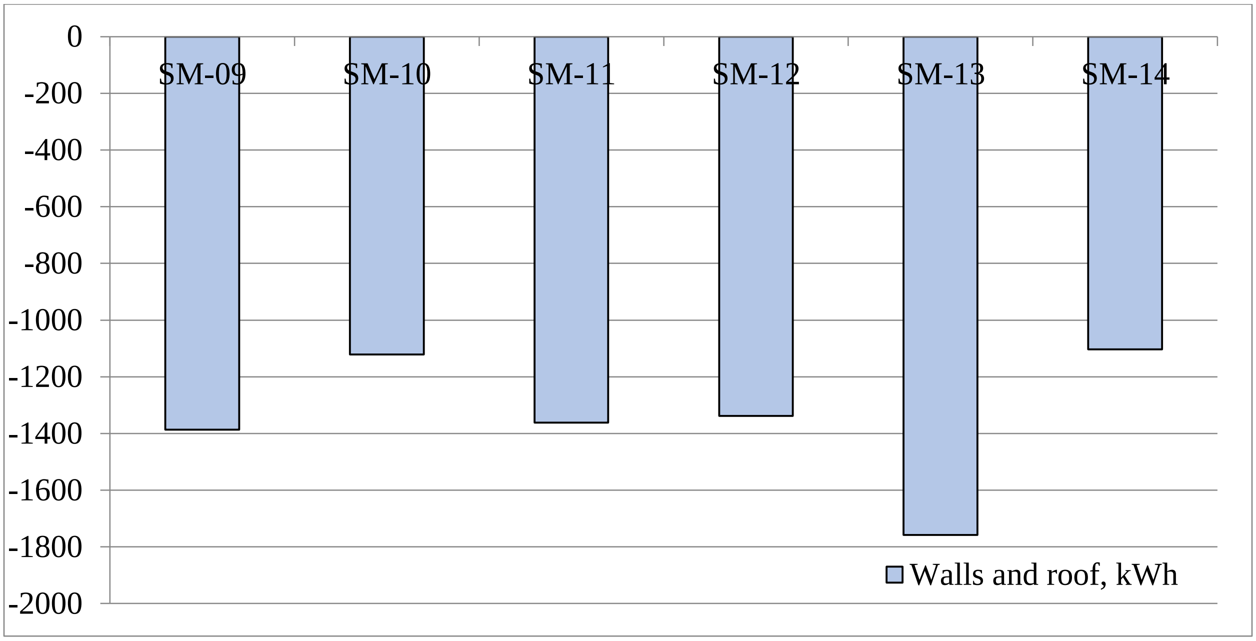


Figure 67: Heat loss from the details of a yurt in heat balance, SM-09 to SM-14.

In *Figure 68*, the thermal comfort of the different materials are compared in terms of occupancy hours during the year are illustrated.

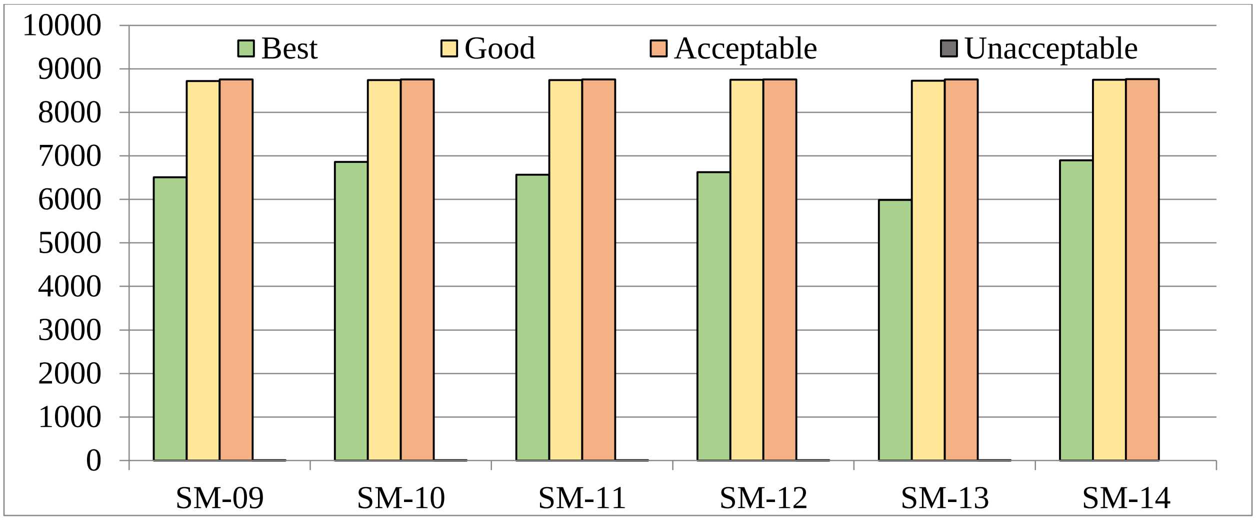


Figure 68: Thermal comfort of the different materials for the yurt with numbers of occupancy hours, SM-09 to SM-14.

5.4. Combination of the Opening and Structural material

From the previous results, OP-03 shows the best opening results for yurt which has large diameter top opening with 3 pane glasses (U-value- 0.7W/m^{2}K) with no window at the wall.

The best result of Structural material character is SM-14 with the tarpaulin (woven waterproof material), Silica aerogel blanket, and PCM, and the total U- value for the wall and roof is 0,1302 W/(m^{2}K). The developments are able to decrease total delivered energy by 2.4 times, and electric heating is also able to be decreased by 30 times. But the cooling is increased to 10 times compared with the existing traditional yurt. In *Table 17* illustrated the delivered energy for the combination of the opening and structural material.

Table 19: Delivered energy for the combination of the opening and structural material.

Meter	Total, kWh	Per m2, kWh/m2	Peak demand, kW
Lighting, facility	306.4	10.94	0.14
Electric cooling	2224.7	79.45	1.032
Electric heating	501.9	17.93	2.132
Equipment, tenant	3153.3	112.6	0.36
Total	6186.3	220.9	3.664

Figure 69 illustrates energy balance results, which show the heat loss from the envelope and thermal bridges, decreased approximately by three times compared with the existing yurt.

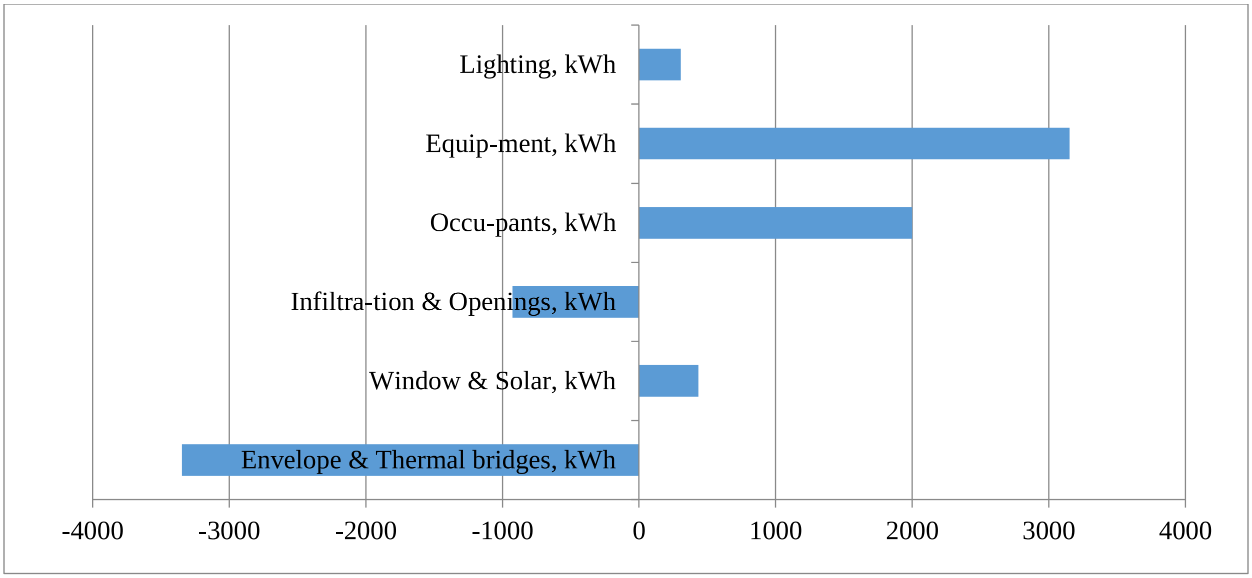


Figure 69: Energy balance for the combination of the opening and structural material.

The heat loss from the envelope area (roof and wall) has been decreased by 7 times compared with an existing yurt. In *Figure 70*, the heat loss from the door is shown to be reduced through the insulation of the Silica aerogel blanket.

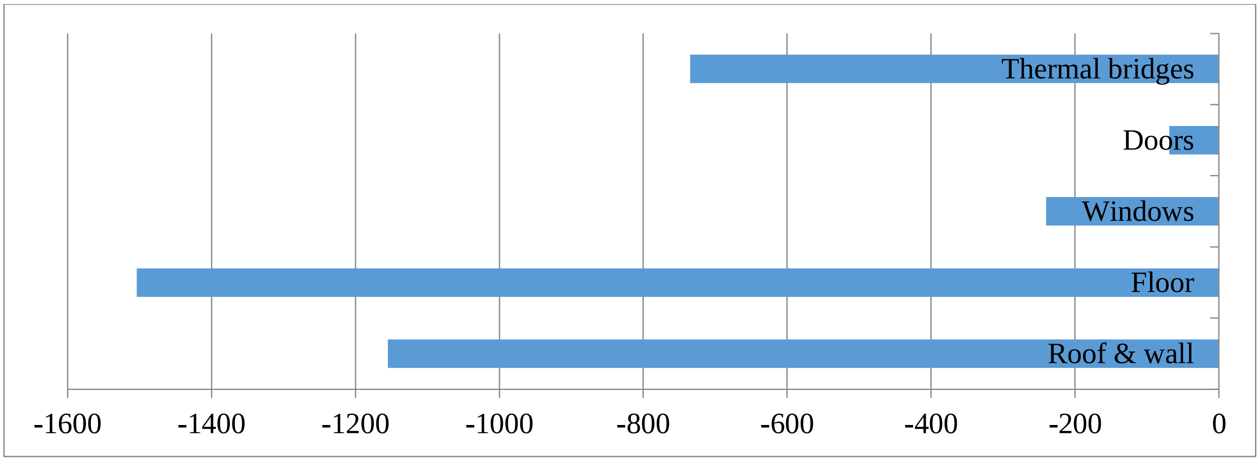
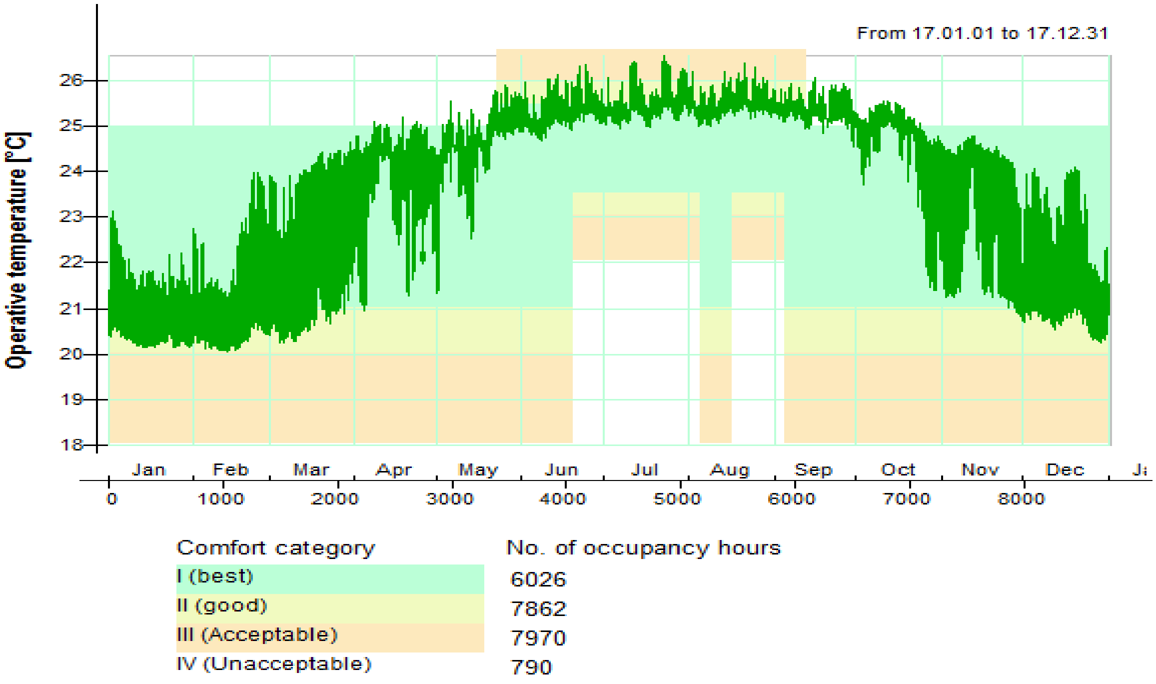


Figure 70: Heat loss and heat gain from the envelope and thermal bridge for the combination of the opening and structural material.

In *Figure 71* illustrated the thermal comfort for the combination of the opening and structural material. The result does not show a high difference in thermal comfort in between the existing, vernacular yurt and the combination yurt due to the simulation model has the same natural ventilation for the calculation.



Comfort category	No. of occupancy hours
🟩 I (best)	6026
🟨 II (good)	7862
🟧 III (Acceptable)	7970
IV (Unacceptable)	790

Figure 71: Thermal comfort for the combination of the opening and structural material.

5.5. Building services systems

The development of the building service systems was carried out in the combined yurt with the optimized opening and optimized structural materials categories.

Heating

The electric heating systems suitable for the yurt are illustrated in *Table 18* along with the number of heater and heater power.

Table 20: Heater types, number of heating and heater power for the yurt.

yurt type	heater type	Number of heaters	Heater power, W
SY-01	Electric radiator	2	2500*2
SY-02	Electric radiator	1	2500
SY-03	Reheat coil	1	2500
SY-04	Electrical floor heating	16m2	2500
SY-05	Electrical heating cooling panel	1	2500
SY-06	Electrical simple fan coil	1	2500
SY-07	Electrical simple fan coil	2	2500*2
SY-08	Electrical floor heating	16m2	5000

From *Table 19*, the result of the minimum temperature and minimum operative temperature shows very low results for SY-04 and SY-08, which potentially caused from floor heating system for the yurt has applied. The floor surface temperature is required to meet an acceptable level as the floor directly contact with the human body. *Table 30* illustrates the minimum (maximum) temperature, minimum (maximum) operative temperature maximum heat supplies, room unit heat of the different heating system for the yurt. The best results on maximum PPD percent are SY-01 and SY-02.

Table 21: Information comparison of the different heating system of the yurt.

	Min temp, °C	Max temp, °C	Min op temp, °C	Max op temp, °C	Max heat supplied, W/m2	Room unit heat, W/m2	Max PPD, %
SY-01	21.03	25.05	20.89	26.53	22.57	82.5	14.1
SY-02	20.34	25.06	20.81	26.67	23.2	81.39	14.6
SY-03	20.38	26.69	19.9	27.14	16.85	71.43	26.38
SY-04	12.76	27.06	14.07	28.97	85.71	85.71	89.99
SY-05	20.94	26.69	20.13	27.13	9.936	67.39	22.51
SY-06	14.99	27.12	15.26	27.48	13.31	89.29	80.7
SY-07	20.66	25.22	20.56	25.75	4.982	64.79	20.39
SY-08	14.51	27.08	15.91	28.97	169.1	178.6	72.59

Table 20 has shown the system heating energy including zone heating, AHU heating and total heating for the yurt with different types of heating. The best results of system energy for the heating are highlighted in grey. SY-01 and SY-02 are the most efficient heating for the system energy.

Table 22: System heating energy differences (Zone heating, AHU heating, total heating).

	SY-01	SY-02	SY-03	SY-04	SY-05	SY-06	SY-07	SY-08
Zone heating	685.9	672.9	735	1204.7	679	0	0	1513.3
AHU heating	0	0	1581.1	0	1584.7	883.5	889.4	0
Total heating	685.9	672.9	2316.1	1204.7	2263.7	883.5	889.4	1513.3

Table 21 has illustrated the delivered energy for the different heating system for the yurt and the grey colored system type is the best result on the table. SY-04 and SY-08 are the highest energy consumption in the delivered energy. The lowest electric heating is SY-01 with an electrical radiator.

Table 23: Delivered energy for the different heating system for the yurt.

Meter	SY-01 Total, kWh	SY-02 Total, kWh	SY-03 Total, kWh	SY-04 Total, kWh	SY-05 Total, kWh	SY-06 Total, kWh	SY-07 Total, kWh	SY-08 Total, kWh
Lighting	306.4	306.4	306.4	306.4	306.4	306.4	306.5	306.4
Electric cooling	2140.7	2386	425.8	2411.5	425.9	726	696.7	2544.2
HVAC aux	0	0	695.2	0	694.3	147	146	0
Electric heating	685.9	672.9	2316.2	1204.7	2263.7	2572.6	2621.5	1513.3
Equipment	3153.3	3153.3	3153.3	3153.3	3153.3	3153.3	3153.3	3153.3
Total	6286.3	6518.6	6896.9	7075.9	6843.6	6905.3	6923.9	7517.2

Figure 72 illustrates the thermal comfort of yurts with the different heating system. SY-04 and SY-08 show very bad results in the floor heating system. The SY-01 shows the best results in thermal comfort for the yurt.

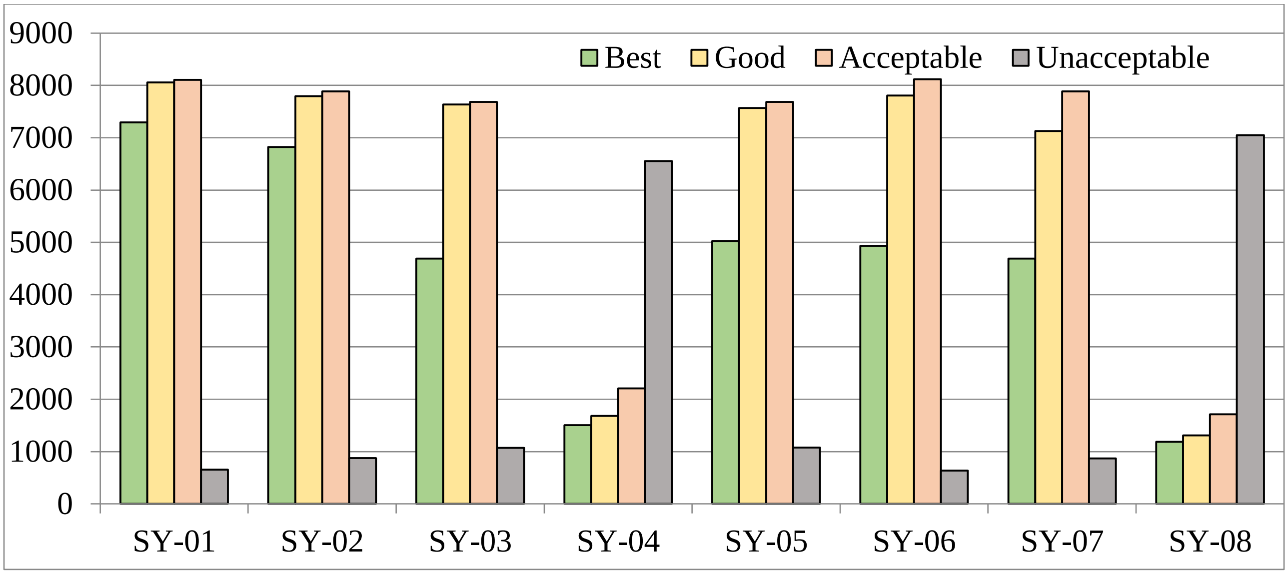


Figure 72: Thermal comfort for the yurts with the different heating system.

Mechanical ventilation

For the ventilation simulation, the combination of natural and mechanical ventilation is tested, whereby the natural ventilation is worked according to the defined schedule. *Table* 22 illustrates different types of AHU for the yurt in the simulation. For the simulation, the cooling element has not set because the natural ventilation is enough for the cooling in summer.

Table 24: Different types of AHU for the yurt.

Yurt types	AHU type
SY-09	Standard air handling unit
SY-10	Electric heat coil
SY-11	Enthalpy wheel AHU
SY-12	Separate set points for heat exchanger and coils
SY-13	Mixing box (recirculation)
SY-14	Return air temperature control
SY-15	Extra heat. Coil (dehumidification)

Table 23 illustrates the general information about yurts with the different AHU systems including minimum and maximum air temperature, operative temperature, maximum supply airflow, maximum return airflow, the maximum age of air and maximum CO_2 volume provided from the simulation result. SY-13 has shown the worst result in the maximum age of air and CO_2 level. Other models have not any big difference between each other from the simulation result.

Table 25: General information of the yurt with different AHU

	Min temp, °C	Max temp, °C	Min op temp, °C	Max op temp, °C	Max sup airflow, L/(s m2)	Max rtn airflow, L/(s m2)	Max age of air, h	Max CO2, ppm (vol)
SY-09	20.84	25.18	20.63	25.68	5.937	5.773	0.3857	903.3
SY-10	20.82	25.17	20.62	25.68	5.956	5.792	0.3857	903.3
SY-11	20.84	25.16	20.63	25.69	5.956	5.796	0.3858	903.4
SY-12	20.82	25.47	20.56	26.05	6.975	6.831	0.3855	903.1
SY-13	20.84	25.27	20.99	25.62	7.093	6.994	2.532	4426
SY-14	20.84	25.16	20.66	25.7	5.267	5.107	0.3858	903.4
SY-15	20.84	25.18	20.63	25.68	5.937	5.773	0.3857	903.3

Table 24 illustrates detailed energy consumption of the AHU, including the energy of heating, cooling, heat recovery, cold recovery, and fans. The best results are highlighted in grey.

Table 26: The energy consumption of the AHU for the yurt.

Yurt types	Heating, kWh	Cooling, kWh	AHU heat recovery, kWh	AHU cold recovery, kWh	Fans, kWh
SY-09	1881	1179.2	3262.4	30.09	563.1
SY-10	1397.3	636.5	3263.7	30.14	452.3
SY-11	224.2	628	4450	38.49	518.2
SY-12	2125.5	1295.6	4138.8	40.02	58.9
SY-13	0.05676	683.6	21015.7	0	174.4
SY-14	4344.5	713.5	0	0	109.3
SY-15	1881	1179.2	3262.4	30.09	563.1

In *Table 25*, SY-11 has the best result in total heating and in the system energy in the setting of different AHU.

Table 27: System energy of the yurt with the different AHU.

	SY-09	SY-10	SY-11	SY-12	SY-13	SY-14	SY-15
Zone heating	1056.2	1055.4	1055.2	873.2	3243.5	1155.2	1056.2
AHU heating	1881	1397.3	224.2	2125.5	0.059	4344.5	1881
AHU cooling	1179.2	636.5	628	1295.6	683.6	713.5	1179.2
Cooling	1179.2	636.5	628	1295.6	683.6	713.5	1179.2
Heating	2937.2	2452.7	1279.4	2998.7	3243.6	5499.7	2937.2

Table 26 illustrates the delivered energy of the yurt with the different AHU and lowest energy consuming result is highlighted in grey. The lighting and equipment tenants are set as constant for all types of yurts.

Table 28: The delivered energy of the yurt with the different AHU.

	SY-09	SY-10	SY-11	SY-12	SY-13	SY-14	SY-15
Electric cooling	1179.2	636.5	628	1295.6	683.6	713.5	1179.2
HVAC aux	568.2	454.1	520.2	64.18	176.4	114.4	568.2
Electric heating	2937.2	2452.6	1279.5	2998.9	3243.5	5499.5	2937.2
Total	8144.4	7003	5887.5	7818.5	7563.3	9787.2	8144.4

In *Figure 73*, the thermal comfort of the yurt with the different AHU is illustrated. The SY-13 has the best result of the thermal comfort and other yurts did not show the high difference as shown in *Figure 73*.

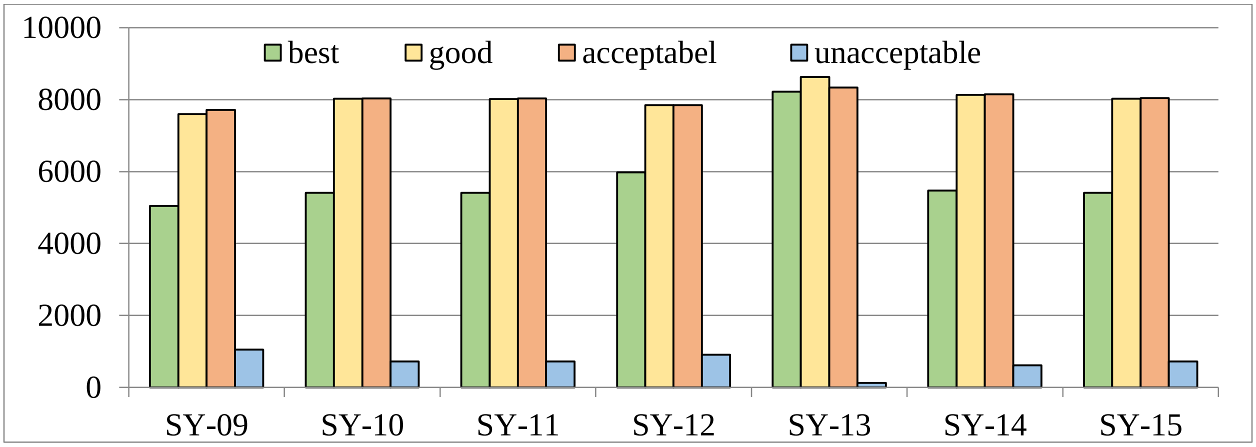


Figure 73: Thermal comfort of the yurt with the different AHU (8760h)

In *Figure 74,* the CO_2 and ppm for the SY-11 have tested as it shows better performance than others. However, the other types of the yurt with different AHU shows the indifferent result in SY-11. Results indicate that AHU improves yurt indoor air quality. The maximum CO_2 level is set 900 ppm in the setpoint of the simulation tool. The CO_2 shows the lower level in summer because the natural ventilation works very well in air exchange.

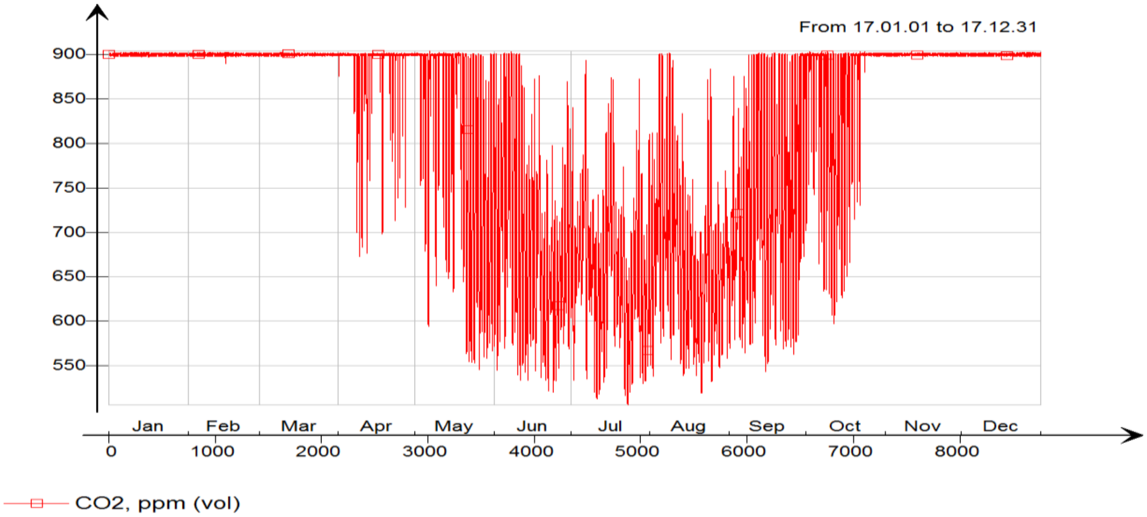


Figure 74: CO2, ppm for the SY-11.

5.6. Conclusions: a potential of the vernacular yurt

Opening

The development simulation has conducted for 11 versions of the opening in two parts. In the first part, the only top opening has tested for 3 different sizes and 2 types of glazing. As a result, OP-03 shows better results than the others which have three pane glasses and with the biggest top opening (1.53 m).

During the heating season, big opening supports the heating through solar gain from entering solar radiation. But during the cooling season, it increases the energy consumption for cooling. In terms of thermal comfort, the results did not show a significant difference compared to the existing yurt. The daylighting of the OP-03 shows much higher results than the other yurts which have a small crown.

The second part has used the window on the envelope following the glazing percentage for the cool climate condition as recommended in (Hausladen, 2012). All windows have three pane glasses with higher U-value. As a result, a smaller window appears to be suitable for the yurt with regards to increased energy efficiency. In terms of energy efficiency, it has found that windows are not suitable for the yurt.

The existing yurt door is made by the solid wood. The development model has applied 12mm of Silica aerogel blanket insulated door, which reduces heat loss from the door by approximately 65 %.

Orientation

Traditionally Mongolian yurt is orientated towards the south. However, simulation results show the orientation of the yurt is not highly affected due to the yurt plan is circle and shape is almost half globe. The yurt has no window and the wall is not flat, the only one window has located the top. The top opening does not affect orientations.

Structural material

The aim of the study is to find the suitable insulation material for the yurt in Mongolian extreme climate. Firstly, lite weight and flexible insulation materials features are compared. For this comparison, all materials thickness has set as same and thermal conductivity, density; specific heat is set as different. The result provides SM-07 and SM-08 is good at heating and but, for the cooling, there is no significant difference found in between the yurts with the different insulation materials. The best-resulted materials are Silica aerogel blanket (SM-07) and vacuum insulation panel (SM-08). The VIP considered as unsuitable for the yurt because the material is not flexible. The Silica aerogel blanket is suitable for the yurt with high U-value and stable to pull up and pull down for the yurt and it is very lightweight material.

Secondly, silica aerogel blanket was simulated at 60mm, 80mm, and 100mm thickness with PCM and compared to find the suitable form of thickness for the yurt. And SM-14 has shown the best result which has 100 mm Silica aerogel blanket, 40 mm PCM, and water protection material. The PCM locates between the poles (uni) and inside of the roof, also in between the wooden wall and insulation material. For the cover material, any material including the tarpaulin, membrane, and Gore-Tex material are suitable with the condition that material should have water and wind protection.

Heating

The electric radiator provides the best result for the heating of yurt which is shown in SY-01. SY-01 shows the best result in thermal comfort result.

Mechanical ventilation

The mechanical ventilation is used in the yurt during the winter season because the natural ventilation cannot work in extremely cold winter at -40 °C outdoor air temperatures. The SY-11 with the Enthalpy wheel AHU shows the best result from the comparison test of the different AHU for the yurt. All AHUs show maximum CO_2 level (900 ppm) as it has set in the simulation tool. Ideal heating has applied in all yurts' simulation. It has found that SY-11 is the most energy efficient model version in system energy and delivered energy results.

6. DEVELOPMENT OF A NEW TRANSPORTABLE, ENERGY POSITIVE RESIDENTIAL BUILDING PROTOTYPE

6.1. Concepts of the transportable dwelling

The yurt can develop three different versions:

1. Combined yurt
2. Modern transportable residential building
3. Migration shelter

Combined yurt

The combined yurt is set in taking account of the best versions of characteristics (OP, OR, SM, SY). The aim of the combined yurt is to keep the traditional way which does not change the form, function, and traditional usage of the yurt. The combined yurt is for herdsman families but the combined yurt is more energy efficient and more comfortable than the traditional yurt.

Modern transportable residential building

Yurt has developed to energy optimized and comfortable modern transportable building. The yurt has been followed to develop some architecture points:

- Flexibility
- Transportable
- Adaptable
- Changeability

The yurt development has been kept from the vernacular architecture which is round shape, top opening, lightweight structure material, and natural ventilation method. Form Chapter 5 modern yurt has used the developed characters, which has been developed using the thermal dynamic simulation and compared each case.

The new yurt can make design separate rooms, moveable interior parts, a buffer zone for the heating and changeable building faces and body. The modern yurt is possible to four different shapes and faces for the four season due to following the function and climate conditions of each season. The yurt’s shape has been more closed in winter and more opened in summer. For the changing season has been easily changeable to shape.

The modern developed yurt should be developed to bigger space due to the traditional yurt is small for the family house. The yurt has been designed without change the shape and structure materials. If the yurt big as to 10m diameter, it can make design 2 levels. But yurt has to be better to one thermal zone due to better to air exchange and radiation temperature effects.

Migration shelter

The yurt can use migration shelter but it should be optimized to natural condition and climate condition. The yurt is more suitable to temperature cool climate zones (Hausladen, 2012). The yurt can make bigger space for public buildings to emergency usage, for example, temporary administration building, emergency station, temporary education building, etc.

The yurt and yurt type of building helpful for people who live in the country have happened to natural disinter, war-torn, an earthquake.

6.2. Results of the development yurt

6.2.1. Combination and optimization of cases

Information and input data of the combined yurt

The combined yurt has developed the main characteristics of the yurt. It has been developed on based of 13th-century Mongolian yurt as it has shown the best result in terms of its shape from comparative analysis for traditional yurts around the world. The detailed information of the combined yurt is expressed in Table 27. Below Table 33 illustrated the elements of the yurt and U-value of elements and heat transfer through elements.

Table 2729: Detailed information of the combined yurt (elements, U-value of elements, heat transfer through elements, and percentage of the heat transfer)

Wind-driven infiltration airflow rate	68.512 l/s at 50.000 Pa			
Building envelope	Area [m2]	U [W/(m2 K)]	U*A [W/K]	% of total
Walls above ground	0.60	0.07	0.04	0.34
Roof	49.58	0.07	3.28	28.40
Floor towards ground	27.73	0.05	1.47	12.71
Floor towards amb. air	0.03	0.07	0.00	0.02
Windows	1.53	1.91	2.92	25.28
Doors	1.42	0.29	0.42	3.60
Thermal bridges			3.42	29.65
Total	80.89	0.14	11.55	100.00

The yurt area is 28 m^2; it follows the dimension of the mainly used herder family's yurt with 5 walls. The volume follows the shape of the yurt; the combined yurt volume is 46m^3. From the result of opening (OP), the yurt has been installed 3 panes glazed window on the top opening (1.54 m2), and the door should be insulated door. The opening and closing schedule of the window and door follows the occupant's usage.

The material of the yurt has kept the traditional wooden frame. However, PCM, Silica aerogel blanket covered by the tarpaulin are applied as a change to traditional materials. The most challenging part of the development of the yurt is that the kind of dwelling has no thermal mass, and the dwelling should be lightweight and high thermal resistant material. The PCM supports to keep the thermal form which is found from the structure material (SM) development result.

The heating and ventilation system has selected to form the best results of the system (SY) analysis.

Results of the combined yurt

Table 28 illustrates the system energy and delivered energy of the combined yurt model.

Table 28: Delivered energy of the combined yurt with the optimized characters.

Meter	Total, kWh	Per m2, kWh/m2	Peak demand, kW
Lighting, facility	306.4	10.94	0.14
Electric cooling	451.4	16.12	1.73
HVAC aux	187.5	6.7	0.13
Electric heating	2092.5	74.7	3.97
Equipment, tenant	1576.65	112.6	0.36
Total	4614.45	164.8	6.329

The energy balance of the combined yurt is shown in *Figure 75*. Highest heat loss is found to be lost through the envelope and thermal bridges.

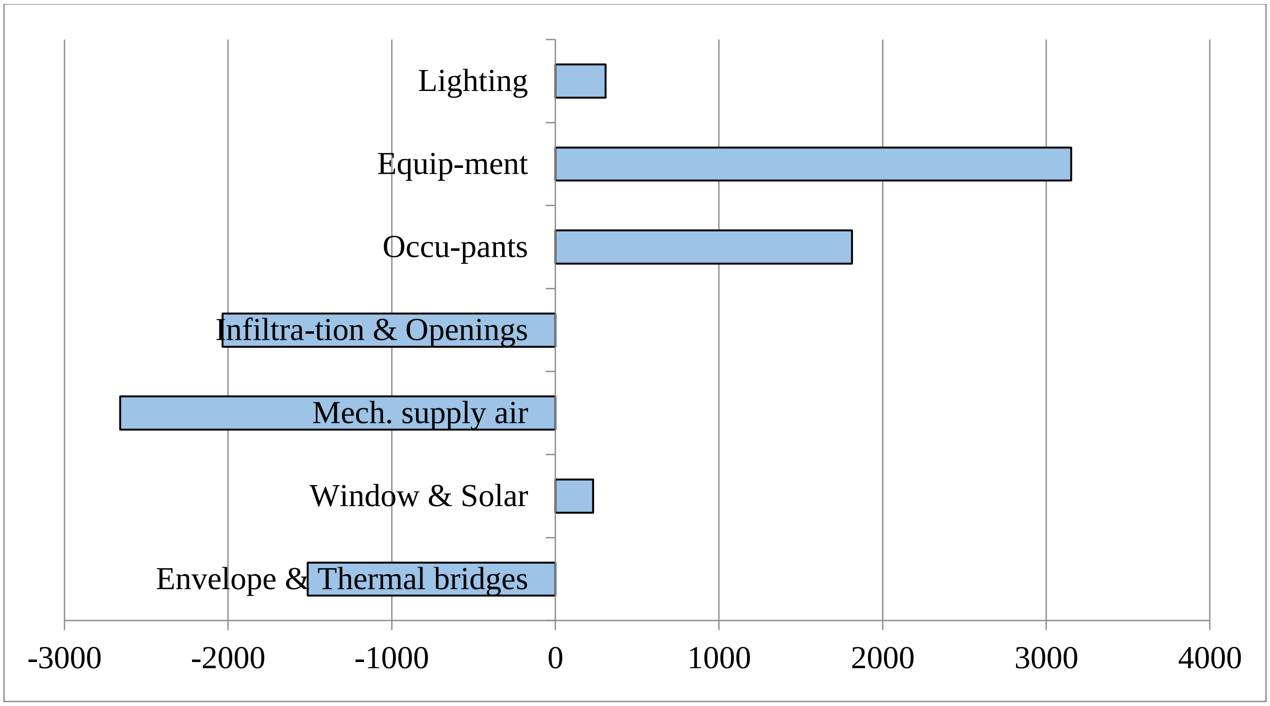


Figure 75: Energy balance of the combined yurt.

Figure 76 shows the envelope heat transmission of the combined yurt. From the result, the heat is mostly lost through the walls and roof.

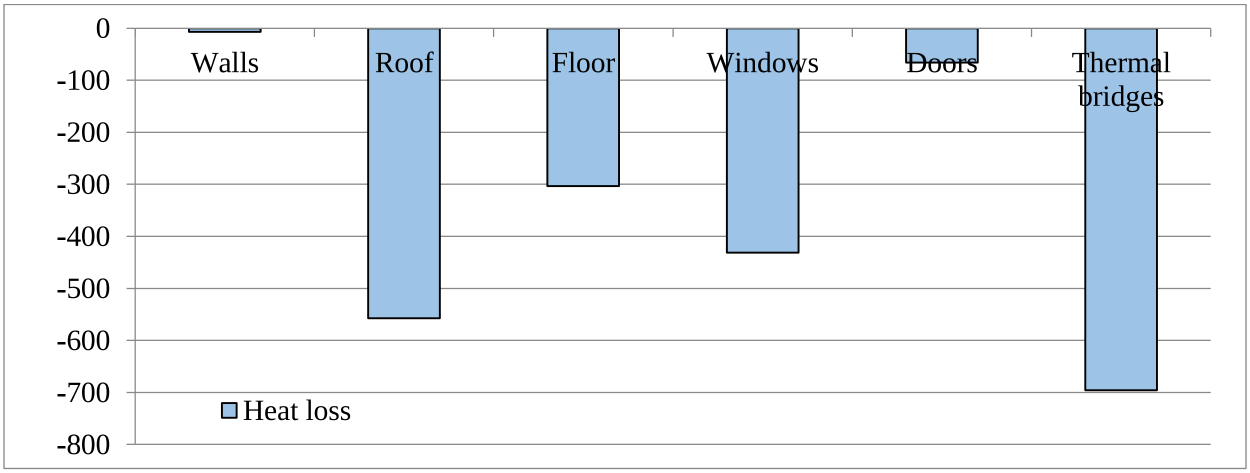
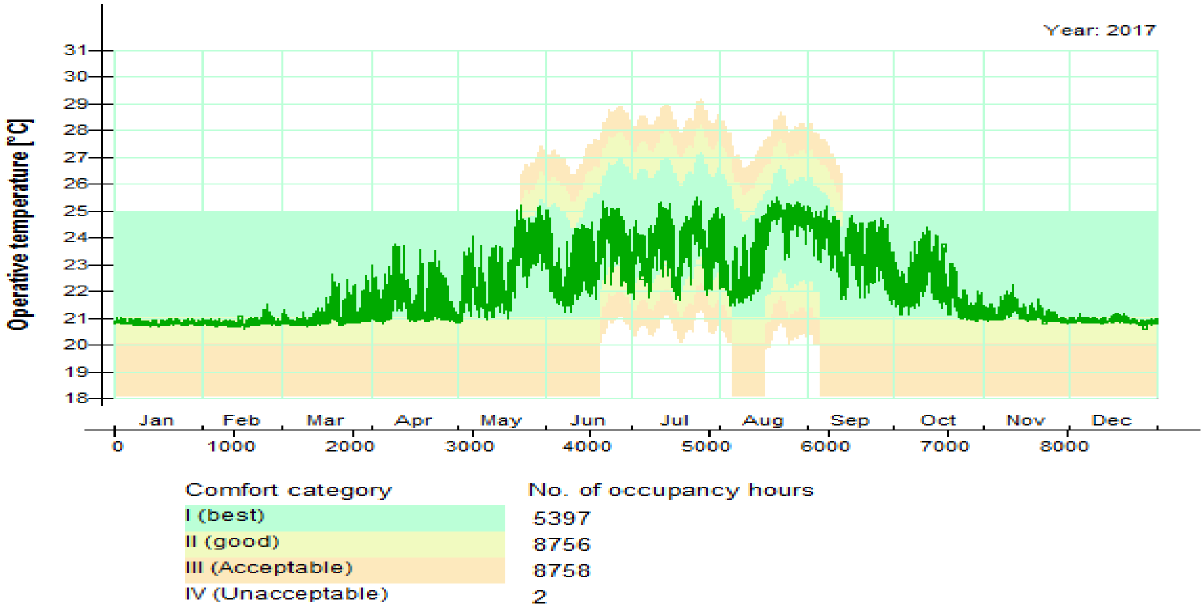


Figure 76: Envelop heat transmission of the combined yurt.

Figure 77 illustrates the thermal comfort of the combined yurt model.



Comfort category	No. of occupancy hours
I (best)	5397
II (good)	8756
III (Acceptable)	8758
IV (Unacceptable)	2

Figure 77: Thermal comfort of the combined model with a distribution of operative temperatures and occupancy hours in comfort categories according to EN 15251 and ISO 7730

Figure 78 illustrates indoor air quality indicated by CO_2, ppm in the circumstance when the air exchange is supported by both of natural and mechanical ventilation and combined model ’s maximum CO_2 level shows less than 720 ppm as shown in the figure.

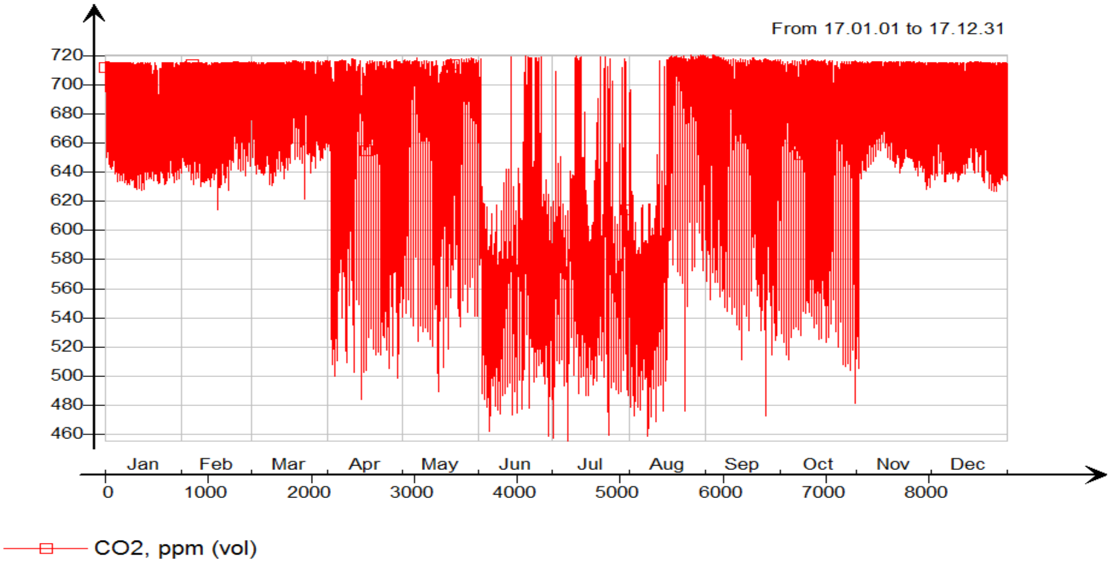


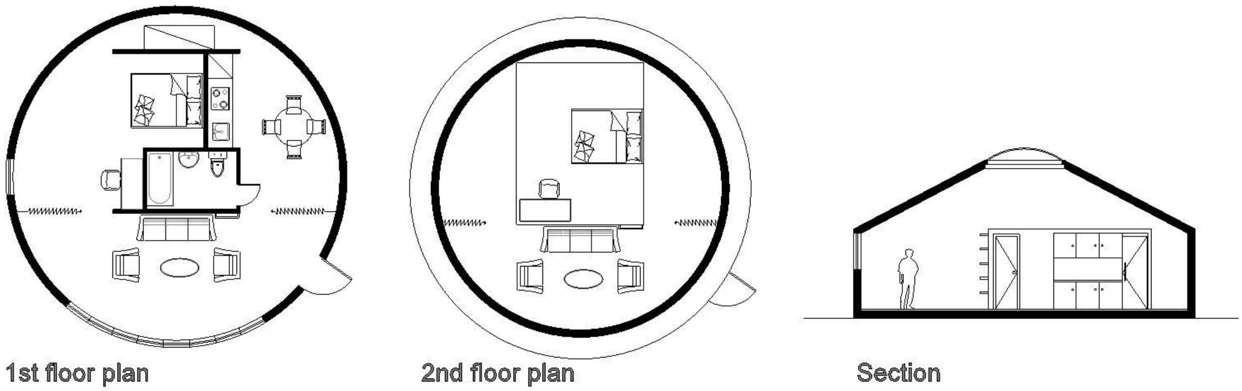
Figure 78: CO_2, ppm of the combined model.

6.2.2. Combination and optimization of cases

Architecture design of the modern yurt

An architecture design for the developed yurt has to keep the traditional yurt shape and structure frame. The traditional yurt in size is tiny for the modern living requirements and yurt has no restroom. The yurt can be enlarged while keeping its shape. Because the dimension of the yurt follows the module where the crown hole is connected with pole sticks (Banzragch, 2006) (Bat-Ulzii.B, 2016).

The developed yurt has a 4.5m radius and 3.9 m height floor to the crown. It can divided to two levels. The yurt is potential to be managed into separate rooms but the wall should be lightweight partition walls. Air exchange of the yurt is made through the crown, khaya, and door called dome chilling effect (M.J.Gorman, 2005). The partition walls located on the center of the yurt make separate rooms. The developed yurt has a living room, kitchen room, bedroom and restroom on the first floor and a bedroom located on the second floor. In Figure 79 illustrated developed yurt's floor layouts and section.


1st floor plan

2nd floor plan

Section

Figure 79: Layouts and section of the developed yurt.

The developed yurt has big windows on the south side, due to support the heating form the solar radiation.

Information and input data of the developed yurt

The simulation model of the developed yurt has one big zone and has some partition walls. Materials of the yurt are the same as the combined yurt due to the material requirement is the same. The plants of the yurt added the 5 m^2 photovoltaic panel installed on the yurt.

Table 29 illustrated the element of the yurt and U-value of elements and heat transfer through elements.

Table 30: Detailed information of developed yurt (elements, U-value of elements, heat transfer through elements, and percentage of the heat transfer)

Building envelope	Area [m2]	U [W/(m2 K)]	U*A [W/K]	% of total
Walls above ground	50.39	0.07	3.35	14.64
Walls below ground	0.00	0.00	0.00	0.00
Roof	67.39	0.07	4.46	19.47
Floor towards ground	0.00	0.00	0.00	0.00
Floor towards amb. air	67.32	0.07	4.39	19.15
Windows	10.10	0.72	7.25	31.66
Doors	2.16	0.22	0.48	2.11
Thermal bridges			2.97	12.98
Total	197.34	0.12	22.90	100.00
Wind-driven infiltration airflow rate	52.836 l/s at 50.000 Pa			

The windows are closed in winter. In other seasonas according to schedule,the opening and closing are managed. In *Figure 80* illustrated the mathematical model of the developed yurt.

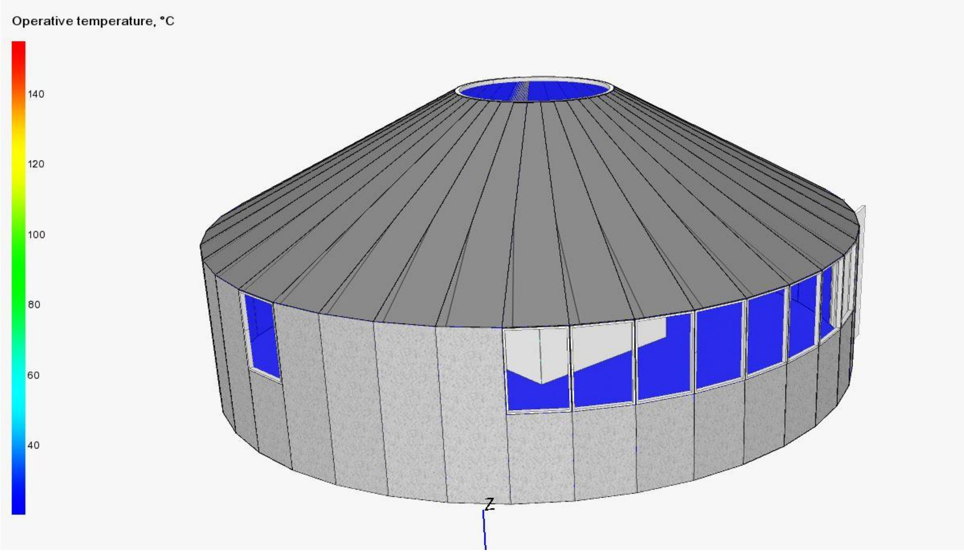


Figure 80: Mathematical model of the developed yurt.

The developed yurt's windows and the door have different schedules for each season. Also, the mechanical ventilation and heating, cooling systems have been worked under different schedules.

Results of the developed yurt

Table 30 expressed the delivered energy of the developed yurt. The highest energy consumption is heating for the yurt but it was much less than the combined yurt's heating. The buffer zone which is set on the south side windows has supported the heating.

Table 31: Delivered energy of the developed yurt

Meter	Total, kWh	Per m2, kWh/m2	Peak demand, kW
Lighting, facility	652,8	8,2	0,18
Electric cooling	57,1	0,7	1,31
HVAC aux	1224,5	15,4	0,3
Electric heating	1686,7	21,3	2,8
Equipment, tenant	1576,65	19,9	0,36
Total	5197,75	65,5	4,61

Local heating units work between January to March and October to December. In January and December, heating is works at the highest load, a smaller amount of the heating needs in March and October (*Figure 81*).

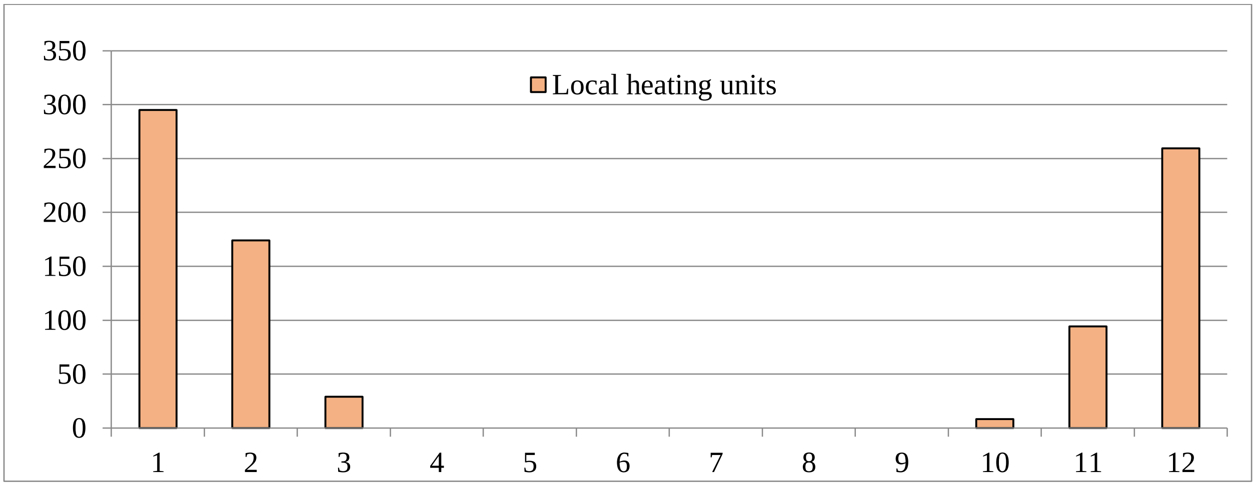


Figure 81: Heating unit for the developed yurt.

Figure 82 illustrates the energy balance of the developed yurt. The result shows the window and solar radiation enables higher heat gain to the yurt, and the most heat loss through the mechanical air supply. The big windows supported heating for the developed yurt.

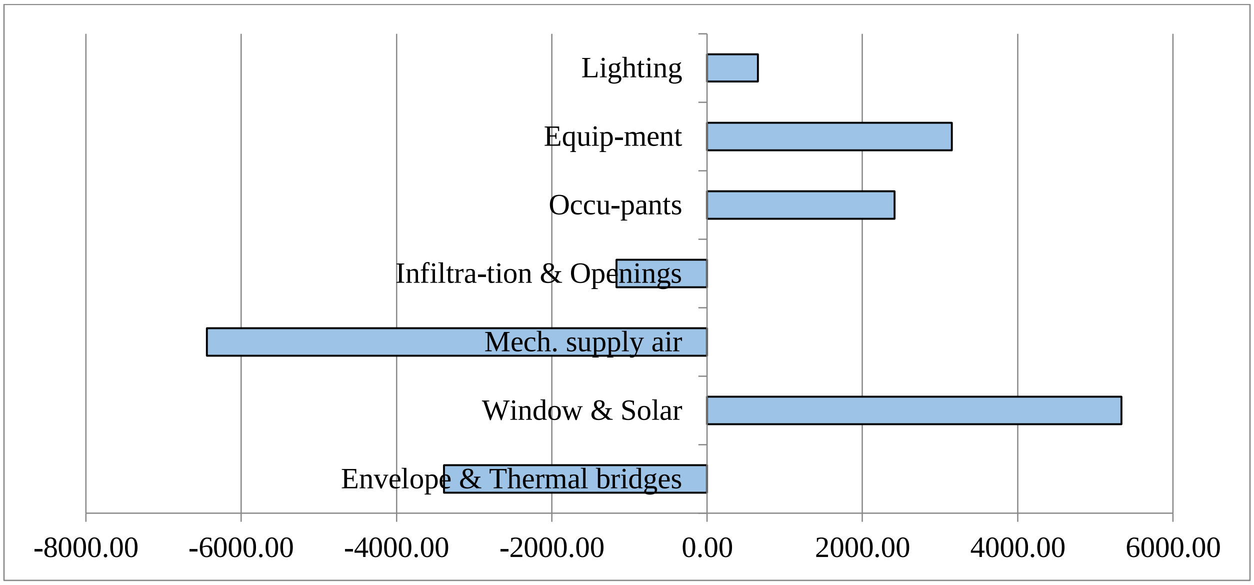


Figure 82: Energy balance for the developed yurt.

The developed yurt is able to manage the heating and cooling by the windows and opennings. While the windows are closed, yurt can be warmed up from the solar radiation through the window and top openinig.

For the cooling, there are two main opennings which are top opening and khaya (lower edge of the wall). In transition season, operation of the opennings are complicated due to severe climate. During summer season, no energy consumption is required for the heating and cooling. It can be manageable through air flow crown, khayaa, and door. The windows needs shading elements.

In Figure 83 illusterated the CO_2 level of the developed yurt. The indoor air quality indicated by the CO_2, ppm.

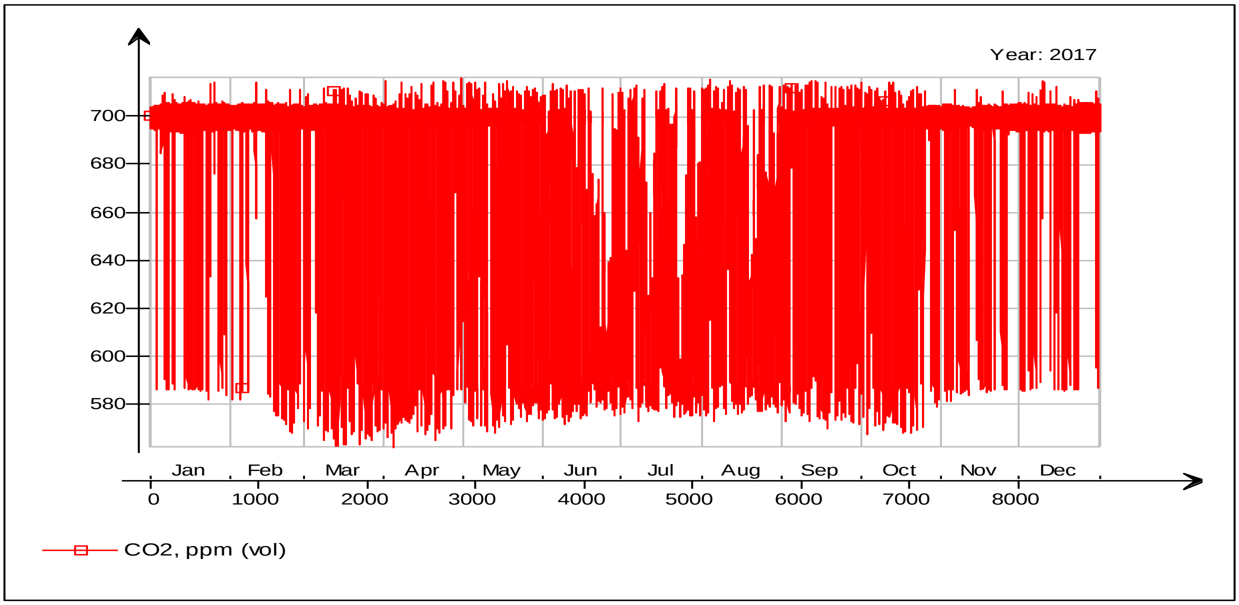
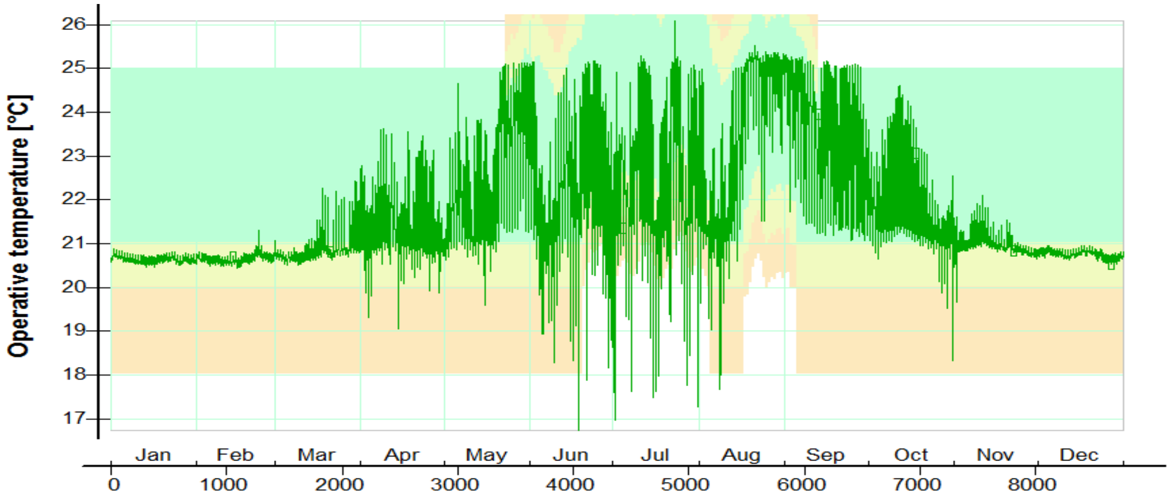


Figure 83: CO_2, ppm of the developed yurt.

Figure 84 shows thermal comfort of the developed yurt with a distribution of operative temperatures and occupancy hours in comfort categories.



Comfort category	No. of occupancy hours
I (best)	4338
II (good)	8358
III (Acceptable)	8619
IV (Unacceptable)	141

Figure 84: Thermal comfort of the developed yurt with a distribution of operative temperatures and occupancy hours in comfort categories according to EN 15251 and ISO 7730

6.3. Conclusions: Optimized combination of an energy positive modern yurt prototypes

Combined yurt

The combined yurt has collected the all best characters including opening, orientation, structures, materials, and systems. The characters are simulated, compared and optimized.

It is investigated that the combined yurt is energy efficient and provides indoor comfort. The unacceptable category of the combined yurt is 12 times lesser than the existing yurt in the thermal comfort results. The best category of the combined yurt is two times higher occupancy hour. than existing yurt's best category of thermal comfort. Indoor air quality is improved through the natural and mechanical ventilation system and it fulfils air quality at an acceptable level as indicated by CO_2 level (460 to 720 ppm).

The combined yurt's energy consumption is 50% lesser than a traditional existing yurt.

Developed yurt

The combined yurt is further improved, in order to design a 'developed yurt' and improvements have been done in the interior and exterior of the yurt. The interior is divided by rooms which transform the yurt into a more functional building and enable manageable operation. The inclusion of rooms or the separation of interior spaces with rooms enabled to install different functions of living needs, including the separate kitchen, living room, bedroom, and bathroom, which fulfil the modern lifestyle. But the all rooms are included in one thermal zone.

Some additional procedures are required to improve daylighting, visual comfort, and natural ventilation. As part of this procedure, windows can be set on outside of the flexible wooden wall. On the south side big windows for the heating and visual comfort. The window should have high U-value (0.7 W/m^2K) and orientation of the window should be optimized.

The energy consumption of the developed yurt shows slightly more energy efficient than the combined yurt from the simulation.

7. CONCLUSION

7.1. Statements

I have investigated different types of traditional yurts. The yurt as a nomadic vernacular architecture has been used in the different natural and climate zones during the thousands of years. The yurt is adaptable and energy efficient low tech dwelling solutions in nomadic cultures. In modern times, even in those nomadic countries, only small numbers of people live in yurt due to urban sprawl. An exception is Mongolia, where 45.4 percent of households live in the yurt. Although there are also examples, when yurts are imported for residential and business purposes into countries, which do not have nomadic culture, the use of yurts has eminent interest in Mongolia. This was the motivation of my research.

As a starting point, I have studied the different type of yurts, and I have identified 9 different shapes of yurts that are used around the world.

For the identification of adaptability and performance of different types of the yurt to the needs of inhabitant and climatic conditions, I have performed their analysis using the thermal dynamic simulation by IDA-ICE 4.8 code. The IDA-ICE 4.8 is a validated simulation tool focused on energy consumption and indoor comfort and climatically parameter input the data.

1. **From the point of view of energy need and comfort, I found that the 13th-century Mongolian yurt has the best shape and performance since that type of yurts needs 28 to 59% lesser energy for ensuring a thermal comfort better than other yurts**.
    - The comparative analysis of the yurt shapes was done in the Mongolian climate conditions. The performance indicators used are the area ratio, energy consumption, energy balance, and indoor comfort.
    - The energy needs for cooling is approximately 10 times less than those for heating under Mongolian climate condition.

Related paper:

- *Gantumur Tsovoodavaa, Rowell Ray Lim Shih, Mohammad Reza Ganjali Bonjar, István Kistelegdi, "A review and systemization of the traditional Mongolian yurt (Ger)", Pollack Periodica, Hungary, 2018.*

- *Gantumur Tsovoodavaa, István Kistelegdi, "Comparative analysis for traditional yurts using thermal dynamic simulations in Mongolian climate", Pollack Periodica, Hungary, 2019.*

2. **It has investigated that the traditional yurt has two main heat loss elements: the envelope area and the top opening. As a result of the simulation, the top opening is found to be the main functional element for the indoor air quality and cooling. The envelope area's insulation material (sheep wool felt) has found to be insufficient for proper insulating of the yurt. It is important since on the basis of these findings several recommendations could be developed for the improvement of these elements.**

The following conditions should be taken into account while identifying the recommendations:

- To further development of the insulation material, it is essential to consider material features to be thin, lightweight, strong and high thermal conductivity as which must meet the transportable, adaptable, and low tech requirement**.**
- The possibility of replacing the top opening with a window would be preferable.

Related paper:

- *Gantumur Tsovoodavaa, Rowell Ray Lim Shih, Mohammad Reza Ganjali Bonjar, István Kistelegdi, "A review and systemization of the traditional Mongolian yurt (Ger)", Pollack Periodica, Hungary, 2018.*

3. **For the development of the yurt to highly energy efficient, high comfort, and modern transportable residential building the following recommendations have been formulated:**

- Considering the top opening, the three-pane glasses show the best result.
    - The top opening generally provides daylight through the skylight, and as a result of development, the more lighting is enabled to be entered.
    - In the summer season, light eternal shading element is recommended.
    - For energy efficiency purpose, no windows on the wall are recommended however, in the case of window setting, it is better to be small as possible.
- The orientation of the yurts did not show high efficiency in relation to its circle layout.
    - However, the south, south-east and southwest orientations have shown slightly better results.

    - The study predicts if the circle layout and shape form is changed, the orientation would have been effective.
- The insulation materials development is the Silica aerogel blanket is best-resulted material for the yurt compared with other insulation material.
    - The optimized the structure of envelope is 40mm PCM, 100mm Silica aerogel blanket and waterproof material.
    - The PCM material has highly affected the cooling but 40mm PCM is suitable for the yurt. Because the yurt should be lightweight structure.
    - The waterproof material can use any materials but the tarpaulin and Gore-Tex material are the best materials for the yurt due to air change with the insulation material.
- It has found that heating electric is more energy efficient than other types of heating systems.
- For ventilation, the Enthalpy wheel AHU is more energy efficient ventilation system for the yurt.

The above options have been selected on the basis of comparative analysis.

<u>*Related paper:*</u>

- *Tsovoodavaa Gantumur, "The material development of the Mongolian yurt using the thermal dynamic simulation" Scientific transactions # 24/251, Mongolian University of Science and Technology, Mongolia, 2019.*

4. **Natural ventilation in the yurt acts as an air exchanger and also cooling the yurt via dome chilling effect from the top opening and lower edge of the wall (khayaa). During summer, natural ventilation can be used for the yurt. However, the operation is important to this time because the openings are mechanically performed for open and close actions. The mechanical operation is preferred than automation in relation to Mongolian severe and unpredictable weather.**
5. **It is justified by analysis, that the yurt resulting after implementation of all recommendations will have better performance in all categories compared to any other types of yurts. The energy consumption is decreased by 80% including the air handling unit.**

6. **To developed and redesigned into modern building requirement in terms of energy positive and high comfortable building while keeping the main functions of adaptable, lightweight and transportable. The developed yurt's size and layout are changeable follow the function, natural and climate condition. It is three times lesser energy consumption than the traditional yurt and has high indoor comfort.**

7.2. Contributions

7.2.1. Scientific contribution

- The prior literature in the yurt was lacking building physics research. This research contributes to transportable residential building literature with the new results and knowledge about the yurt.
- This research gives good direction for future research on transportable and energy efficient residential building.

7.2.2. Social contribution

- The developed transportable residential building is very environment-friendly. The yurt locates on the soil, but after the movement of the yurt, soil can be renewable. The energy used for yurt is without the carbon dioxide which supports renewable energy source.
- The transportable residential building has developed with high indoor comfort and energy efficient for the nomadic people. All energy requirements in a yurt can be provided with renewable energy sources.
- The other countries especially located in a cool climate zone can apply this developed transportable building. The building has simulated and optimized in the most extreme climate zone of Mongolia which has the temperature gap of 80°C in between summer and winter.
- Yurt can be utilized for temporary housing in all other countries not only limited by nomadic cultures with various purposes. In addition to tourism and traveling, it can be used in severe conditions including post-natural disaster situations and war zones, etc.

7.2.3. Architecture contribution

- For this research, the nomadic architectural heritage of yurt is not changed from its view.

- It has found that nomadic vernacular residential building shape contributes to energy efficient building requirement and green architecture.

7.3. Future directions

- In the future, it is fruitful to validate the simulated yurt model with a measured yurt.
- It is crucial to building a real yurt in Mongolian site applying the developed yurt concepts and proof testing measurement of the research outcomes on indoor comfort and energy consumption.
- It will be useful to examine the yurt's aerodynamic using the CFD simulation. The shape of the yurt aerodynamic is interesting as it can stand during the strong wind without any hard connections with the earth. And the inside air flow is very important for natural ventilation.
- In the future development of the yurt will redesign and optimize to provide higher standards and certificates of the green building.
- Yurt will have possibele to make migration shelter for the any climate and any different natural condition.

<u>List of Publications by Tsovoodavaa Gantumur</u>
Information as of April 30, 2019

<u>Published:</u>

1. A review and systemization of the traditional Mongolian yurt (Ger)

Author: Gantumur Tsovoodavaa, Rowell Ray Lim Shih, Mohammad Reza Ganjali Bonjar, István Kistelegdi
Journal: Pollack Periodica, Hungary.

2. Comparative analysis for traditional yurts using thermal dynamic simulations in Mongolian climate

Author: Gantumur Tsovoodavaa, István Kistelegdi
Journal: Pollack Periodica, Hungary

3. Comfort and energy performance analysis of a heritage residential building in Shanghai

Author: Chu Xiaohui, Ganjali Bonjar Mohammad Reza, Gantumur Tsovoodavaa, Rowell Ray Lim Shih, Balint Baranyai
Journal: Pollack Periodica, Hungary

4. Importance of developing Ulaanbaatar regional for the site in sustainable development and optimal setting of the capital city

Author: Gombo. J, Ulziisuren.D, Tsovoodavaa.G
Journal: Scientific transactions # 08/155, School of Civil Engineering and Architecture, Mongolian University of Science and Technology, Ulaanbaatar, Mongolia, 2014, ISBN 1560-8794
Language: Mongolian

5. Energie-Design-Fachplanung in einem Tech-Lab-Projekt: Planungsunterstützung in Form von thermischen und strö- mungstechnischen Simulationen anhand eines Fallbeispiels „NOÉ“ Tech-Lab an der Universität Pécs, Ungarn

Author: István Kistelegdi, Bálint Bachmann, Gabriella Medvegy, Tsovoodavaa Gantumur, Mohammad Reza Bonjar Ganjali, Bálint Baranyai, István Ervin Háber
Book: Bautenschutz, Nachweismathoden und Anwendungen, Germany, 2018, ISBN 978-3-00-060009-8
Language: German

6. The material development of the Mongolian yurt using the thermal dynamic simulation

Author: Tsovoodavaa Gantumur
Journal: Scientific transactions # 24/251, Mongolian University of Science and Technology, Ulaanbaatar, 2019, ISBN 1560-8794
Language: Mongolian

Published in conference proceeding:

1. The widening of the walkway and the cycleway

Author: Byambajargal.B, Tsovoodavaa.G
Conference: Scientific conference in land administration and urban design
Journal: Scientific conference proceeding in land administration and urban design, Ulaanbaatar, 2014 *(Full paper)*

2. The study of measuring the thermal and energy consumption of the Mongolian yurt

Author: Munkhbat.E, Tsovoodavaa.G
Conference: Doctoral and master course student symposium, 25 March 2019
Journal: Scientific transactions # 25/252, 2019, ISBN 1560-8794 *(Full paper)*
Language: Mongolian

3. Hungarian active house, refurbishment, dynamic thermal simulation, energy analysis

Author: Tsovoodavaa Gantumur, Istvan Kistelegdi
Conference: 12th Miklos Ivanyi International PhD and DLA symposium, 3-4 November 2016
Journal: 12th Miklos Ivanyi International PhD and DLA symposium, University of Pecs, Hungary, ISBN 978-963-429-094-0 *(Abstract)*

4. Review and systemization of the traditional yurt

Author: Tsovoodavaa Gantumur, Istvan Kistelegdi
Conference: 13th Miklos Ivanyi International PhD and DLA symposium, 3-4 November 2017
Journal: 13th Miklos Ivanyi International PhD and DLA symposium, University of Pecs, Hungary, ISBN 978-963-642-780-1 *(Abstract)*

5. The aesthetic and effects of contemporary, digital arts in architecture

Author: Urnukh Darizav, Tsovoodavaa Gantumur
Conference: TDK Rezume PTE MIK 2017
Journal: TDK Rezume PTE MIK 2017, University of Pecs, Hungary *(Abstract)*

6. Comparative analysis for traditional yurts using dynamic simulation in Mongolian climate

Author: Tsovoodavaa Gantumur, Istvan Kistelegdi
Conference: 14th Miklos Ivanyi International PhD and DLA symposium, 29-30 October 2018
Journal: 14th Miklos Ivanyi International PhD and DLA symposium, University of Pecs, Hungary, ISBN 978-963-429-284-5 *(Abstract)*

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