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

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by

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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 fulfill the set of objective, as an 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.

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

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Tsovoodavaa Gantumur

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	IDA- Indoor Climate and Energy
N	North
S	South
W	West
E	East
NE	North East
NW	North West
SE	South East
SW	South West

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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[1]. 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. However, there is a lack of researches in the transportable building sector. The transportable building is the 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 'yurt' which is common and fundamental for nomads. The main features of yurt are portable, ergonomic and environmentally friendly which fits for the purpose of dealing environmental problems as well as human shelter needs. The yurt structure, materials, and operations have not been significantly changed since ancient times. However in this modern society where the people's requirements on living standard, comfort, and social needs are incomparably changed and increased from those back to thousands of years. And there is a lack of prior study on indoor comfort and energy consumption on yurts.

Research objective

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

Goals

To fulfill 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, the thermal dynamic simulation will be performed for different shapes of a yurt in Mongolian climate setting.
3. To identify the most efficient and comfortable yurt, 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 used in the thermal dynamic simulation tool.
4. Find the yurts with optimal characters from the simulation.
5. Collect the characters which optimal characters to the yurt and make a new yurt collected the best-resulted characters from the simulation.
6. Developing transportable, adapted, energy efficient and low tech solution which meets modern architectural concepts.
7. To find the optimal transportable residential building in the extreme changes in climate zones, develop the traditional vernacular architecture, used by the validated professional thermal dynamic simulation tool with the high resolution of climate data.

Research questions

- Does current yurt provide indoor comfort which meets the modern living standard of occupants?
- How can we develop yurt to make it more energy efficient and comfort?
- How to achieve today’s energy consumption and indoor comfort requirement in an existing yurt?
- What has to be changed, replaced, redesigned, and modified on a traditional yurt to develop a modern building development?

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 zone and expected to be useful for other cool climate countries as Mongolian climate is one of the severe and extreme condition.

Initial points of research

1. In Mongolian context, the yurt is widely used accommodation in respect to both of the nomadic and residential living style which relate to the country's 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, comforts as the complementary attribute to portability have 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 comfortableness of yurt is demanded.

Initial problems

1. Mongolian climate has a significant temperature difference of 80 ºC in between summer and winter.
2. So far, the nomadic and transportable building has not studied from a building physic science.
3. During the history, the traditional vernacular yurt was only developed from its decoration and changes in minor details.

4. Today 45% of households live in a yurt and 29% of whole yurts are not connected to electricity supply in Mongolia (*Table 1*), [2]

Table 1: Total percentage of Mongolian households without electricity (Source: World Bank. 2006),[2]

	total	Houses without electricity	Yurts without electricity
Ulaanbaatar	3643	938	2705
province center	9881	1524	8357
Villages	2478	830	1648
Soum center	16630	5281	11348
Outer rural households	144552	11711	132841
Total	177552	20284	156900
% of Total households/ yurts in Mongolia		4%	29%

5. The yurt has no heating system and household burn the wood, coal and other materials for the heating in cold seasons which contributes to the biggest problem of pollution in the capital city and other areas of Mongolia. The thermal comfort of the yurt is not an approvable category in the winter due to yurt has not heated.
6. The materials used for yurt structure have not necessarily changed during the history and for the people who live in a yurt in contemporary, yurt does not provide the necessary comfort
7. The yurt must maintain its transportability to fit for a nomadic lifestyle. Hence, it can’t apply big building service systems and the potential changes to yurt must consider lightweight, fast and easy assembly.

1.2.Research method and structure

Research method

The main body of research will apply the simulation method. The thesis will cover 4 separate but interlinked groups of researches.

1. Literature review. As the initial research, the related literature on the transportable building, vernacular nomadic residential building will be reviewed and discussion will be included in Chapter 2. In Chapter 3, the literature on climate design of the transportable residential building in the cool climate zone will be reviewed and discussed.
2. Comparative analysis. Comparative analysis will be held for the different shapes of traditional vernacular yurts and which will be examined for Mongolian climate zones. For this analysis, the simulation tool will be applied for the energy and indoor comfort of the different shapes of the yurt with the same boundary conditions. And the study will be discussed in Chapter 4.
3. Optimal characteristic yurt development. On the basis of results received from Chapter 4, 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. And Chapter 5 will demonstrate this process and discussion.
4. On the basis of previous studies discussed in prior chapters, new prototype concepts on the transportable residential building will be designed. And concepts will be simulated for ensuring the prototype as an optimal solution.

Research structure

In below *Figure 1*, the research structure is demonstrated in a diagrammatic form.

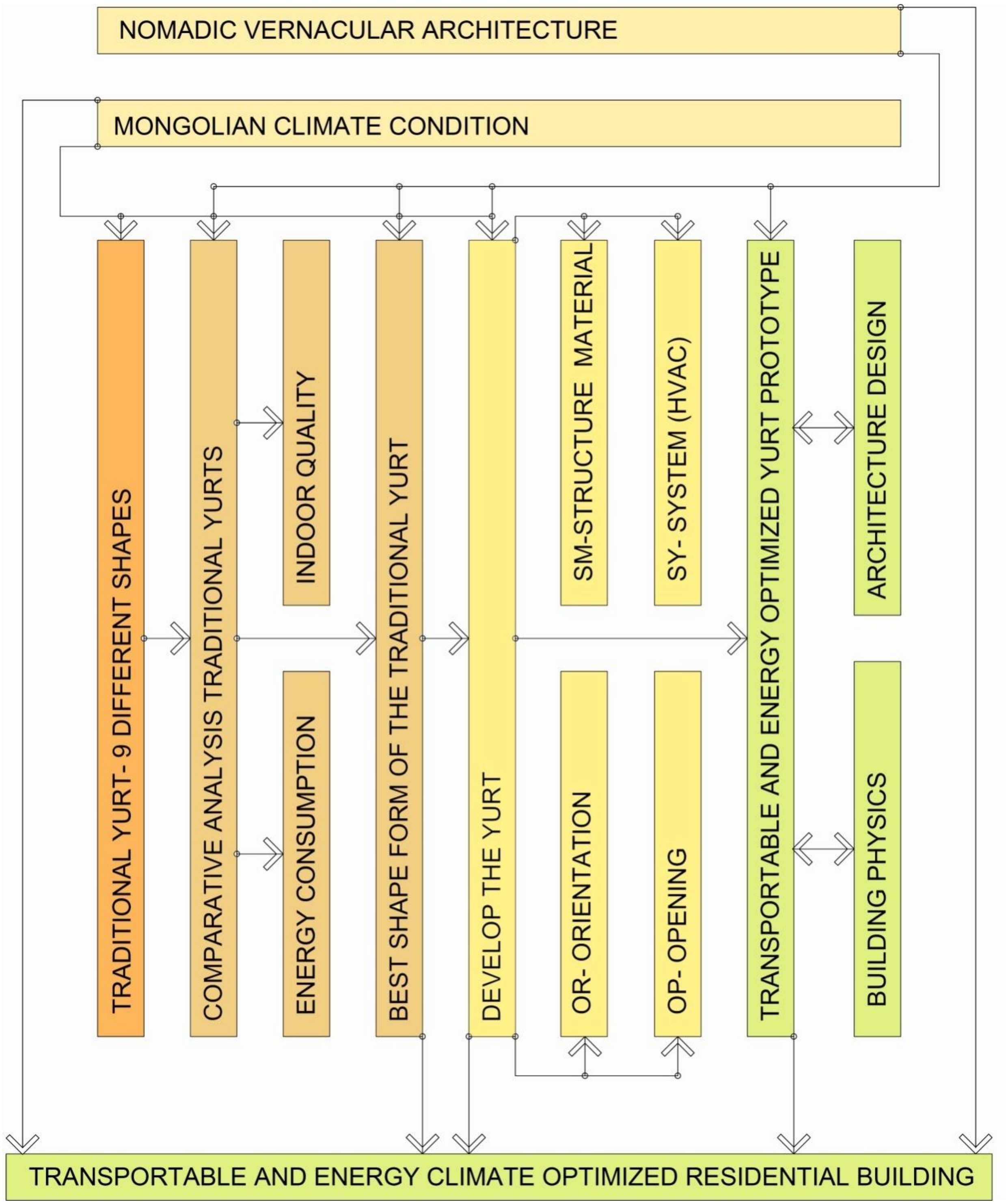

Figure 1: Research structure diagram for the topic.

1.3.Overview of Mongolia

The main research field 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.

Historical overview

Some of the oldest monuments known as *hun-chuluu* (human-stone) aging 3000 years are found from Mongolian territory and which is deemed as Mongolian historical heritage[3]. Also, the historical findings related to the first nomadic state Hunnu empire (Xiongnu or Huns existed during BC 209) proves the people of the state used to live in Mongolian steppe [4][5][6][7]. Historians view Hunnu had a big influence on its neighbor countries through trading and ruling[8]. Southern neighbor China built the Great Wall against attack from nomadic horseman military army around 7^{th} century BC [6][8]. Hunnu Empire kept its dominance for five centuries in the central Asian area which covers the territory from India to Hungary in terms of modern landscape [9][10][5]. After the fall of the Hunnu Empire, nomadic states of Xianbei, Tureg, and Uigar were founded [1][11].

In consideration of key historical events related to Mongolia, the Great Mongol Empire was founded by world well-known king Chinggis Khaan in 1206, which is the biggest empire in the world history[8][10][12]. The population of the empire was just under one million at time of formation and which was then grown to 100 million [8][12]. During Chinggis Khaan's reign, the roots of 'Silk Road' was established which enabled the exchange of cultural and political development through world trade started from Karakorum – capital city of Mongolian Empire– until the Islamic Caliphate's monopoly. The economic roots were established during that time and people get used the standardized money [8][12]. Trade and communication increased between Asia and Europe creating new routes, ports, cities, laws and educational systems [8]. Later, Chinggis Khaan's grandson Khubilai founded Yuan Dynasty (1213-1293) and built the city of Beijing [8][12]. As wells as in the overlapped timing, the Golden Horde Empire (1237-1480) which was ruled by Batu Khan and Jochi, who were the grandsons of Chinggis Khaan established the city of Moscow which is now the capital city of Russia [106]. And in the west, the side the state of Chagatai Khanate (1225-1680) and Ilkhanate (1256-1353) states existed [12][13].

After the struggle of Great Mongol Empire in the 14th century, scions have settled in territories of modern Russia and ‘kzstan’ countries, Inner Mongolia, and Turkey [8]. And around 17th century Manchu Empire (1611-1911) was started to set the rule in Mongolia for 220 years. In 1911, Mongolia was returned back the Independence from Manchu [8]. And afterward, Mongolian Independence was recognized internationally in 1921. In 1924, Mongolia has become the Mongolian People’s Republic and was declared as Socialist country which lasted for almost 70 years until the end of 1989[3]. In 1990, Mongolia has declared the democracy which was one of the most peaceful transitions.

Contemporary Mongolia

Mongolia is a landlocked country located in 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[8]. The population is 3,057,778 [14] of which 87.4 thousand live abroad and 49.2 % of the population is male and 50.8% is female[14][15]68% of the population lives in urban and 32% live in rural areas in Mongolia (*Figure 2*).

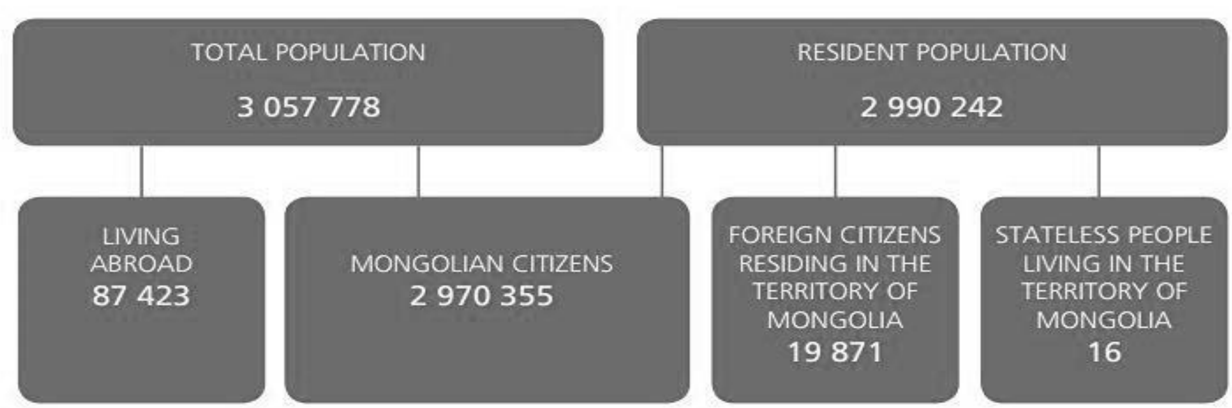

Figure 2: Population of Mongolia, 2015 [15].

In below *Figure 3*, the households' housing type statistics is shown that 45.4 percent of the households live in Mongolian traditional yurt of which 49 percent of households live in the city[15].

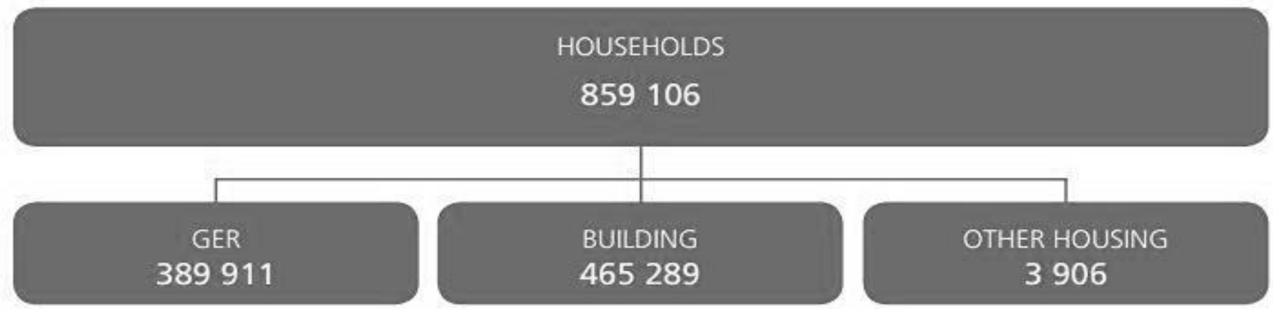

Figure 3: Households housing types of Mongolia.

Overview of climate, geographical and climate zones of Mongolia

Climate overview: Between the latitudes of 40º north and 60 º north is a cool temperature climate with full humidity is found in the northern hemisphere [16].

Air temperature: Mongolian climate has a very high-temperature difference between summer and winter in relation to the continental location [26].Mongolian air temperature ranges between 10ºC and 26.7 ºC in summer and -15 ºC and -30 ºC in winter[17][18][19]Mean temperature in the mountain area lower than -4 ºC, between mountains and big rivers, lower than -6 ºC to -8 ºC. In the steppes and desert regions it is lower than 20C, while in south Gobi desert, the average temperature is higher than 6 ºC [19].

The coldest month is January which averages -30 ºC to – 34 ºC in the high mountain areas of Altai, Khangai, Khuvsgul, and Khentii; while it is -20 to -25 ºC in the steppe and -15 to -20 ºC in the Gobi desert. In 1940 the coldest temperature record was -55.3 ºC in December 1976 at the Zuungovi sum, Uvs province, while it is -49.0 ºC in the capital city of Ulaanbaatar in December 1954 [18],[19].

Precipitation: Precipitation is low in Mongolia; annual mean precipitation is 300-400 mm in the Khangai, Khentein and Khuvsgul mountainous regions, 250-300 mm in Mongol Altai and forest-steppe zone, 150-250 mm in the steppe zone and 50-100 mm in the Gobi-desert [19]. The potential evapotranspiration is less than 500 mm in the mountain regions, 550-700 mm in the forest-steppe zone, 800-900 mm in the forest-steppe, 650-750 mm in the steppe zone, and 800-1,000 mm in the desert-steppe and desert zone [18][19]. During the winter months, approximately 10 mm of snow falls in the desert, 20-30 mm in the mountains and the Uvs lake depression and 10-20 mm in the other regions [18][19].

Sunshine: Mongolia receives an average of 230-260 days of sunshine annually, which is 2,600-3,300 hours of sunshine a year [19].

Winds: Mongolian steppe and desert steppe zones are very windy. Annual average wind speed in these areas is in 4-6 m/s, and the other areas are 2-3 m/s. Wind speed is in 1-2 m/s in the Khentii mountain valleys and the other areas are around 2-3 m/s. The Gobi-desert zone is 41.3% of Mongolian entire land. Around 61% of dust storm occurs in March, while 7% occurs in summer. According to the observation, 300-600 hours of dust storm occurs in a year in the Gobi-desert one. Mongolian dust storms are one of the main sources of “Asian yellow dust” [19].

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 [17][18]. It is surrounded by high mountains and exists at 1,580m altitude and the highest point is Nairamdal peak, Tavan Bogd Mountain which is elevated 4,374m above the sea. The lowest point is Khukh nuur (Blue Lake) with 552 m altitude [17][18][19].

Natural zones: There are 6 different geographical zones in Mongolia [20]which are illustrated in below *Figure 4*.

Alpine or high mountain zone: The high mountain zone covers only 5 percent of Mongolian entire territory and which consists of Altai, Khangai, Khentii and Khuvsgul Mountains [17][18]. 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 [17].

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.

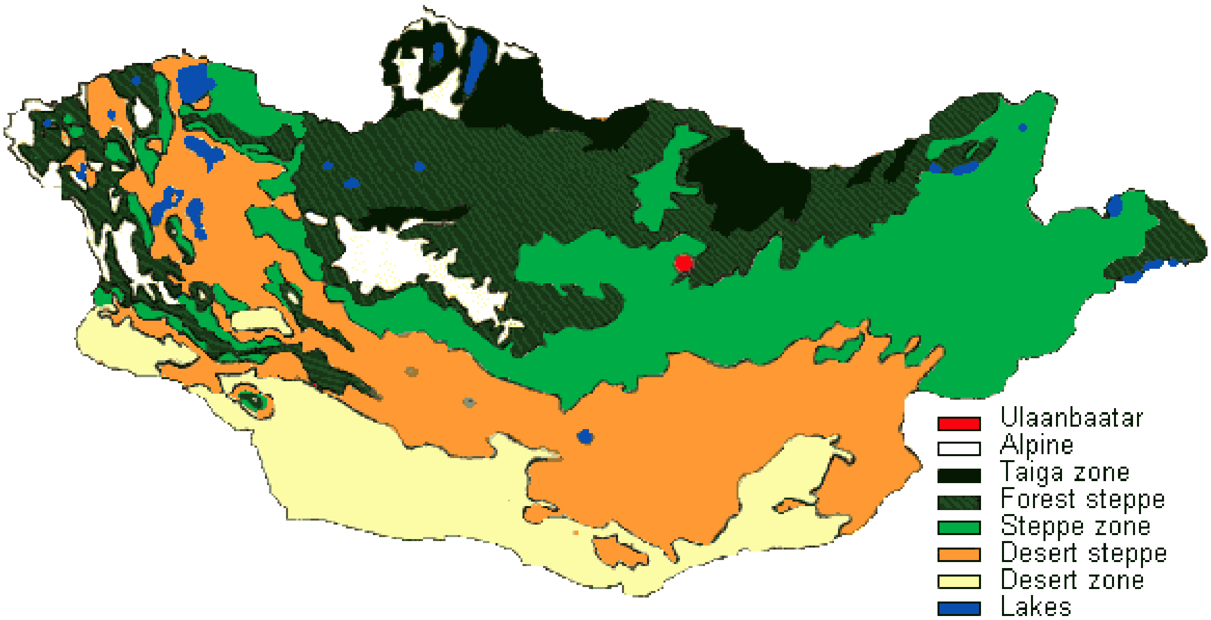

Figure 4: Natural geographical zones in Mongolia

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 is interchangeably existed 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.

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 groups 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

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

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 which shows lower than 100mm per annum. The wind speed reaches 140 km per hour and dust storm is dangerous during spring and fall.

Climate outline

Between the latitudes of 40º north and 60 º north, cool temperature climate zone is found in the northern hemisphere [16].

Air temperature: Mongolian climate has a very high-temperature variance between summer and winter in relation to its continental location [16]. Mongolian air temperature ranges between 10ºC and 26.7 ºC in summer and -15 ºC and -30 ºC in winter [17][18][19]. 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 south Gobi desert, the average temperature is higher than 6 ºC [19].

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 [18][19].

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 [10]. In the winter season, the snowfall level ranges between 10 mm to 30 mm depending on the climate zone [18][19].

Sunshine: Mongolia is a relatively sunny place where it has 230-260 days of sunshine per annum. And on an hourly calculation, it takes 2,600 to 3,300 hours of sunshine per year [19].

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 5*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.

In*Table 2* climate and the geographic information is systemized on cases of chosen climate stations from all climate zones and subzones.

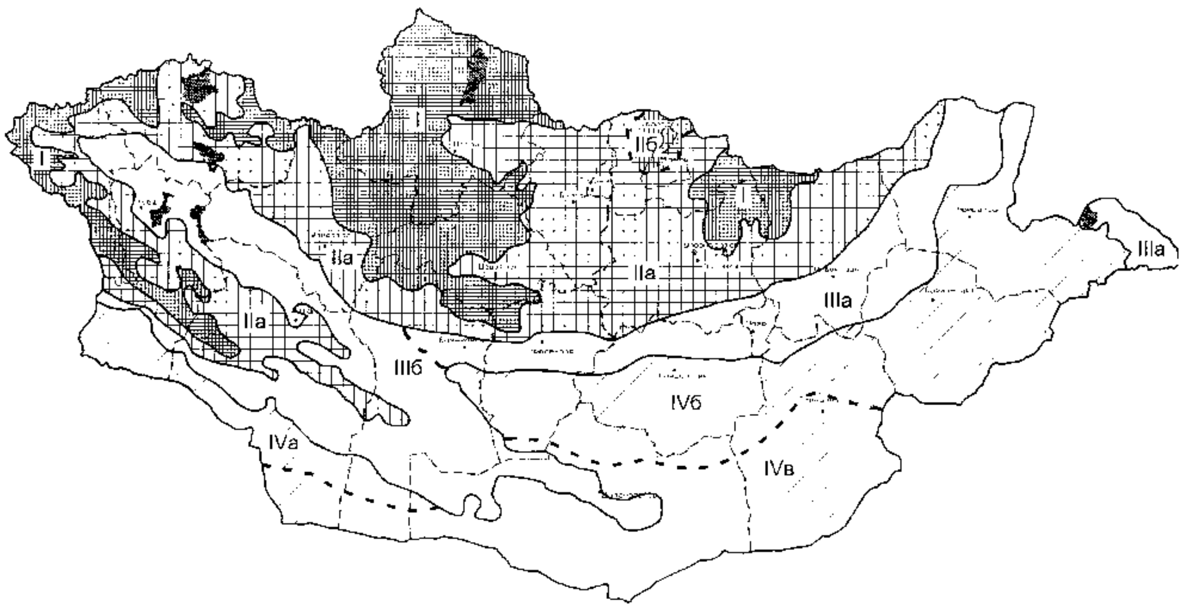

Figure 5: Climate zones for urban planning [21]

Table 2: Climate zones based on 'Meteonorm' climate database [22] [2].

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

2. TRANSPORTABLE BUILDING, RELATED PAPER: A REVIEW AND SYSTEMIZATION OF THE TRADITIONAL MONGOLIAN YURT (GER)

2.1. Introduction to the chapter

One of the ancient structures made by a 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 [10][23][24][25]. 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. On the basis of its unique design supported by passive ventilation system called as 'dome chilling effect' [25], the yurt enables people's comfort in any climate. The Mongolian yurt module is set up by the dimensions of crown holes for the poles[10] and the size of the yurt associates with the size of the crown which usually holds the radius proportion of 4:1[10][24]. 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 [10][26][27]. The entire structure can be fully packed and transported by camel, yak and in modern days by a small car

2.2. 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 drawing from the cave inscription in the Bugat soum, Uvurkhangai province, and Tsagaan Salaa, Bayan-Ulgii province of Mongolia [10]. During the Hunnu empire existence, BC 4^{th} to the 1^{st} 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 [10][11][28][27][29].

In the book of Professor Daajav, 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 [10]. 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 next nomadic states of Xianbei, Tureg, and Uigar for their basic shelter[10][11][30]. 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 [10]. 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 [11]. 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 [10]. The yurt originally had felt 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 [10][25][26].

2.3. Structures and materials

The traditional yurt generally has two main parts, including a collapsible wooden frame and cover with sheep wool felt which are discussed in the next subsections separately. *Figure 6* illustrated details of the traditional Mongolian yurt.

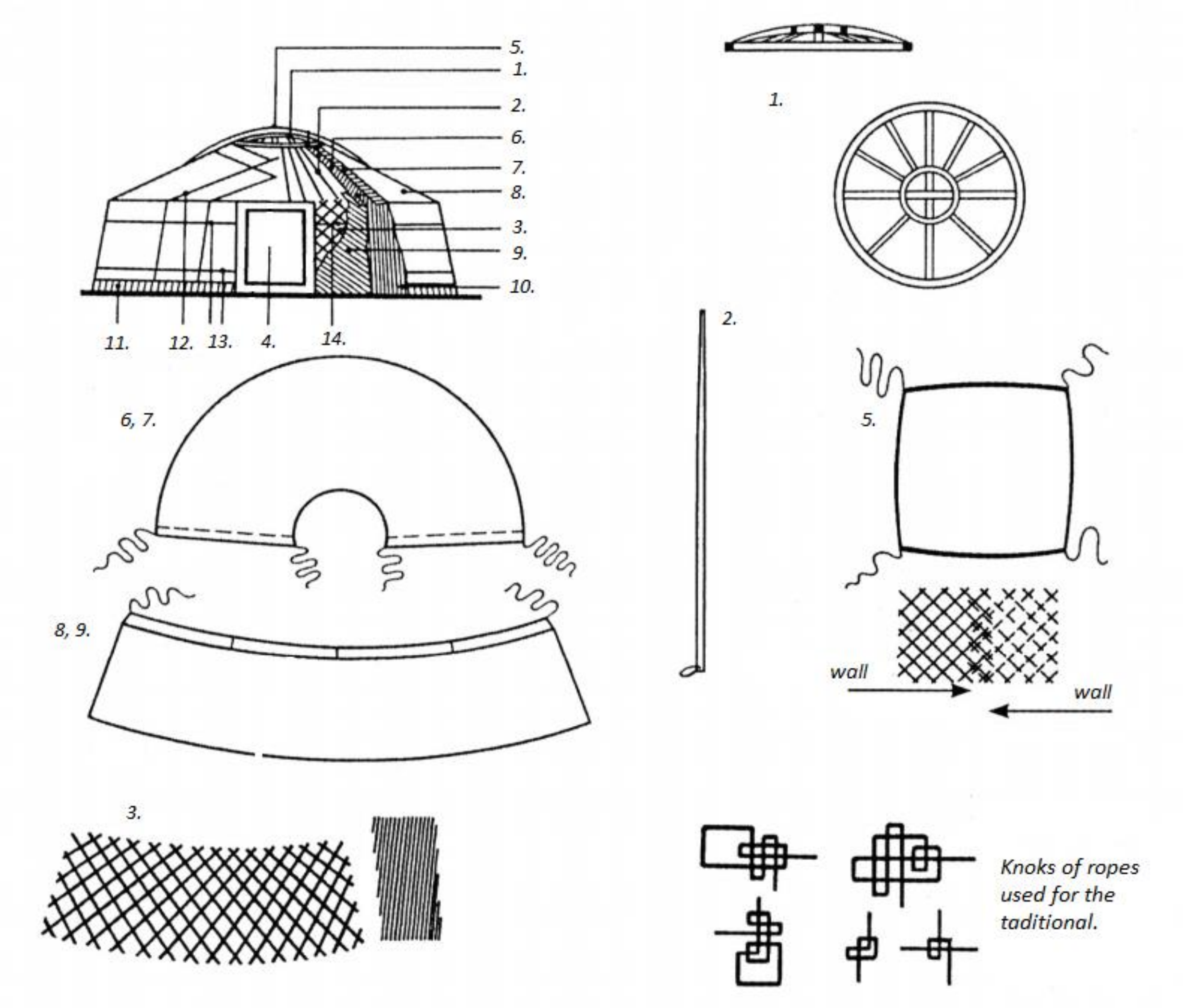

Figure 6: Materials of the traditional Mongolian yurt, wooden frame: 1. Toono-crown, 2.Uni-poles, 3. Walls, 4. Door. Felt cover: 5. Urkh, 6. Inside felt roof, 7. Outside felt roof, 8. Coverage, 9. Inside felt the wall, 10. Outside the felt wall,11. Khayaavch- felt or wooden boards closing off the lower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

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Dimension s of the yurt

The yurt dimension is connected to each detail; the most important element is the crown. The yurt follows the crown diameter and form. Below *Table 3* systemized the yurt dimension with the numbers of walls diameter of the crown, the diameter of the yurt, height of column and area of the yurt.

Table 3: Detailed dimension of the yurt.

number of walls, m	number of uni, m	Crown's diameter, m	Yurt's diameter, m	Height of columns, m	Height of the roof, m	Area of the yurt, m²	Volume o f the yurt, m³
4	64	1,22	4,9	1,95	0,74	18,1	29
		1,02	4,1	1,65	0,63	13,1	17
5	81	1,54	6,1	2,5	0,96	29,3	58,6
		1,28	5,1	2,07	0,79	20,6	33,5
6	96	1,82	7,3	2,94	1,12	42	96
		1,52	6,1	2,46	0,94	29	56,7
7	11	2,12	8,5	3,42	1,3	57	153,3
		1,78	7	2,88	1,1	38,9	88
8	128	2,4	9,6	3,88	1,48	72,6	223,7
		2	8	3,24	1,24	50,2	128
9	141	2,56	10,2	4,14	1,58	79	257,6
		2,12	8,5	3,43	1,31	56,5	152,2
10	160	3,08	12,3	4,97	1,89	119	467,9
		2,56	10,2	4,15	1,59	82,3	251,4
11	173	3,28	13,1	5,3	2,02	135	556,8
		2,7	10,8	4,37	1,67	91,6	313,4
12	192	3,64	14,5	5,9	2,26	165	758,6
		3,02	12,1	4,88	1,86	114,6	439,5

Collapsible wooden frame

The collapsible wooden frame includes crown, poles, walls, door, and the upholder columns.

Crown (Toono): The crown is the only circle shaped window of the yurt located at the top which is covered by the felt roof. It supports the entire structure, and enables light admittance as well as has a function of ventilation. The crown is connected to the lattice walls through the poles. Depending on the area climate, different materials are used for the crown. Since ancient times, pressed wood made of birch wood and brushwood [26][31] were used to make a crown, but larch wood was not used for crown making in Mongolia as it is heavy, easy to be damaged and attracts thunder. In recent times, the crown used in Mongolia, Inner Mongolia and the United States of

America becomes steady and glue the parts to make compounded. The different types of crowns are shown in *(Figure 7)*[10][26].

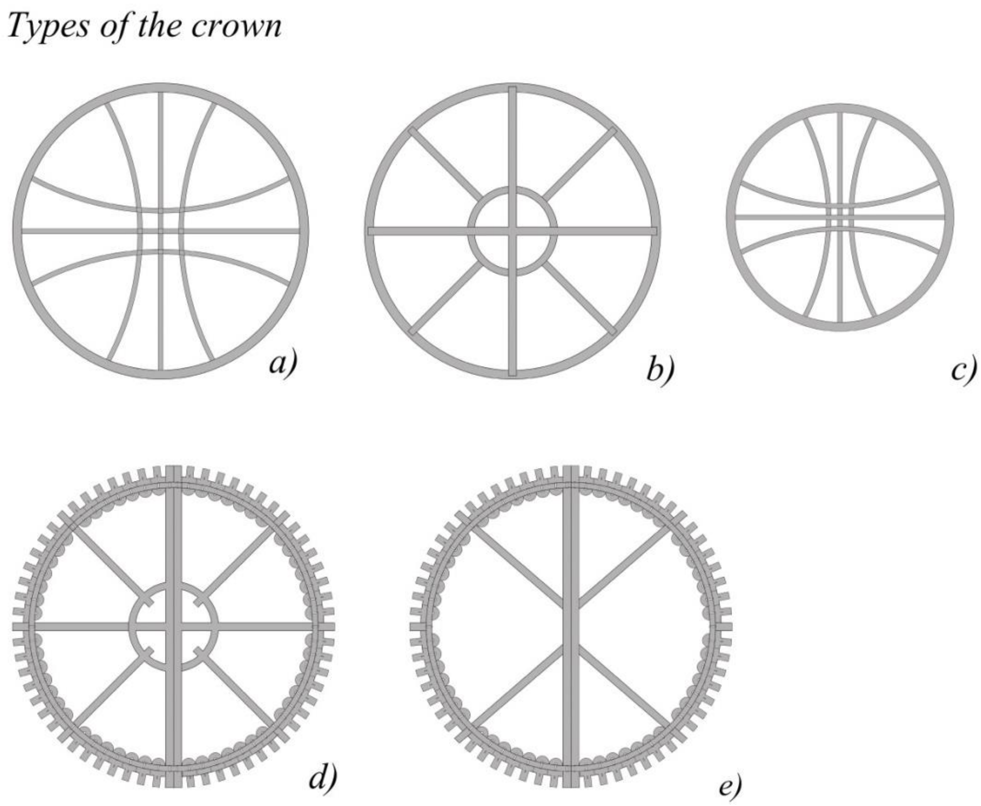

Figure 7: a) Saraalj crown, b) Khorol crown, c) High and small Saraalj crown, d) Khorol crown with trussed wood, e) Separable crown (Sarkhinag)

<u>Poles (Uni)</u>: The poles are usually made of wooden sticks which are used to connect crown with walls [25]. And the number of poles depends on a number of walls, in other words, size of the yurt, which ranges between 64 and 192 for the number of walls between 4 and 12 respectively [10]. And the poles support the felt roof.

<u>*Walls*</u>*:* The wall transmits the compression weight on to the soil, while the wooden lattice makes the walls collapsible. The walls are bound through the holes at the edges by cattle processed skin which strengthens the exterior of the yurt. The number of walls includes: 4, 5, 6, 8, 10 and 12 and those are connected to the door.

<u>*Door*</u>*:* In the ancient times, felt shutter was used for door and which had the easy operation of lifting up or down for opening and closing. Currently, the felt was replaced to the wooden door

which makes the door as the heaviest part in the yurt. And the nomads use either one or two doors.

Column: Columns are the main vertical supporters of the yurt which is located at the center of the yurt. The yurts with 4, 5, 6 walls have two upholding columns and those with 8, 10, 12 walls have four columns. Columns support the crown from the bottom and safely secure all components of the yurt.

Felt covering

All areas of the yurt including walls, crown, and poles are covered by felt. The felt crown cover is called *urkh*. The felt is made by the mixture of sheep wool and hair of life stock animals. Earlier, felt was colored by the paintings made of limestone processed from bone for getting the white color. For waterproofing, processed goat fat was used as it absorbs to the felt and plaster.
Finally, felt covers are protected by three belts set around the wall parts.

2.4. Types of yurts

There are various types of yurts used around the world. The types are varied by its purpose: commercial, tourism and residential. It has found that 31 countries use yurts with different purposes as illustrated in *Figure 8* and out of which 13 of them uses their traditional yurt. The climate of areas had a huge effect on changing the design and shape of the yurt and the basic form of yurt has evolved for specific countries [32].

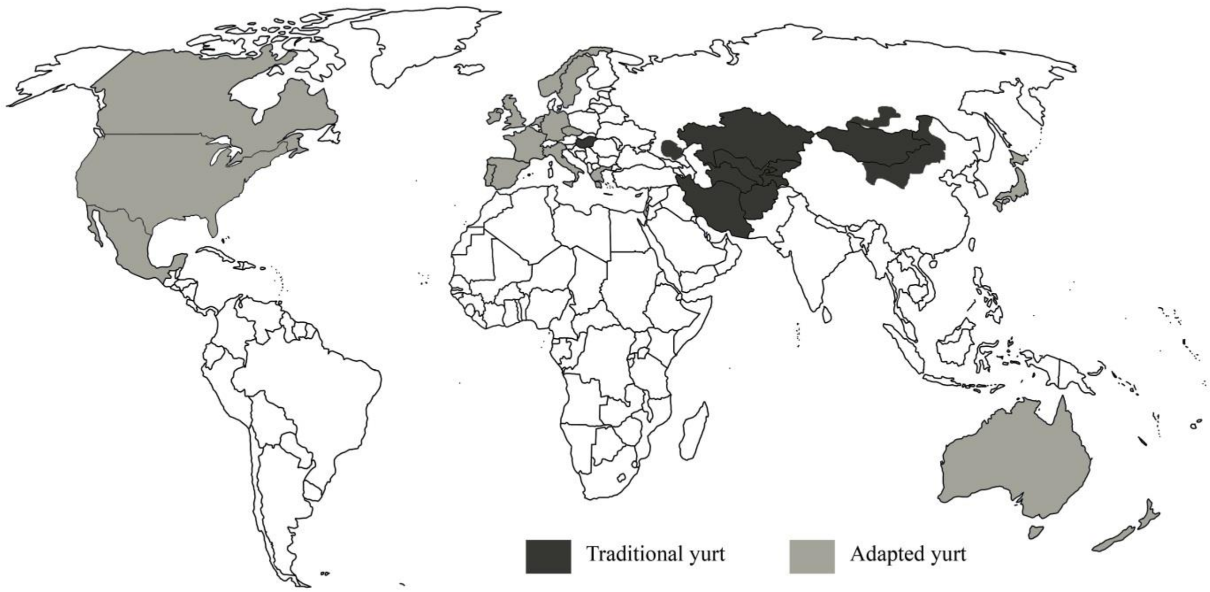

Figure 8: The location map of traditional and adapted yurt in use today

The locally originated (Mongolian) yurt was developed by the traditional means. And in the other countries from region to region alternative designs appear. In *Figure 9* 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.

Mongolian Yurt: Since the 1900s, the modern Mongolian yurt form has shaped and which is identically used by Mongolians and other Mongolian tribes who are now living in neighboring countries. For example, the yurts used in Kalmyk (live in Russia) and Buryatia (live in the south side of Russia) tribes are same as modern Mongolian yurt. The modern yurt has started to apply religious symbols, that the crown has turned out to 'Khorol' crown as shown in *Figure 7* and wooden parts have started to be carved. Also, the artistic qualities were applied during this time and the users choose varying artistic expressions. The Mongolian yurt (*Figure 9*) is considered to be the most developed yurt in terms of the largest, steadiest, and most decorated yurt in relation to its consistent use since the ancient times and in relation to that[10][26][33].

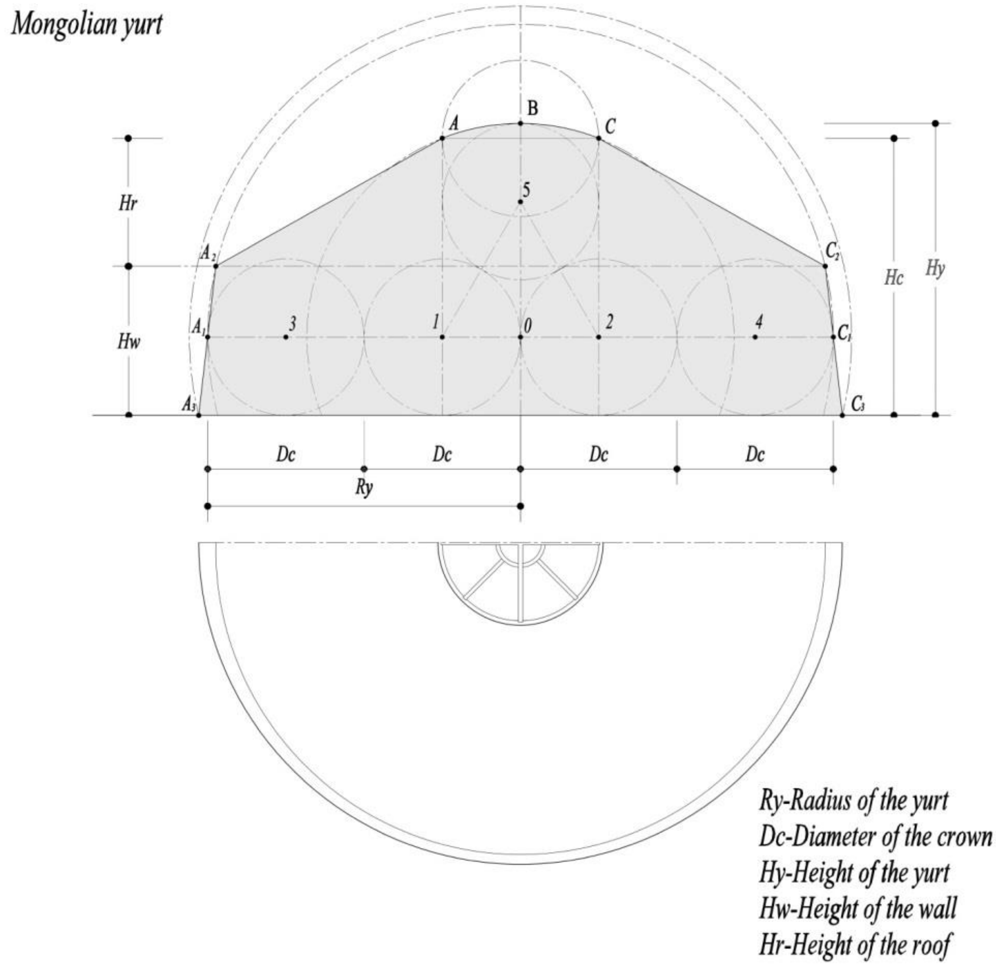

Figure 9: The Classic form of a Mongolian Yurt

<u>Hunnu Yurt</u>: TheHunnu yurt is the most ancient dome-shaped yurt among the other yurts. The poles are curved like an arc and the crown was composed of two connected arches of the same size (*Figure 10*). Currently, many countries have adopted this type of crown (*Figure 7*), which is called the 'Saraalj' crown [10][26].

<u>Mongolian Empire Yurt</u>: The Mongolian Empire yurt is varied from the others for its double crown, which is much better at smoke extraversion (*Figure 10*) and enables more stability; hence the oxen carts with the yurts were moved without pulling down the entire structure. And this change in yurt has led to the origin of new varieties and functions of yurt during the time [10][26].

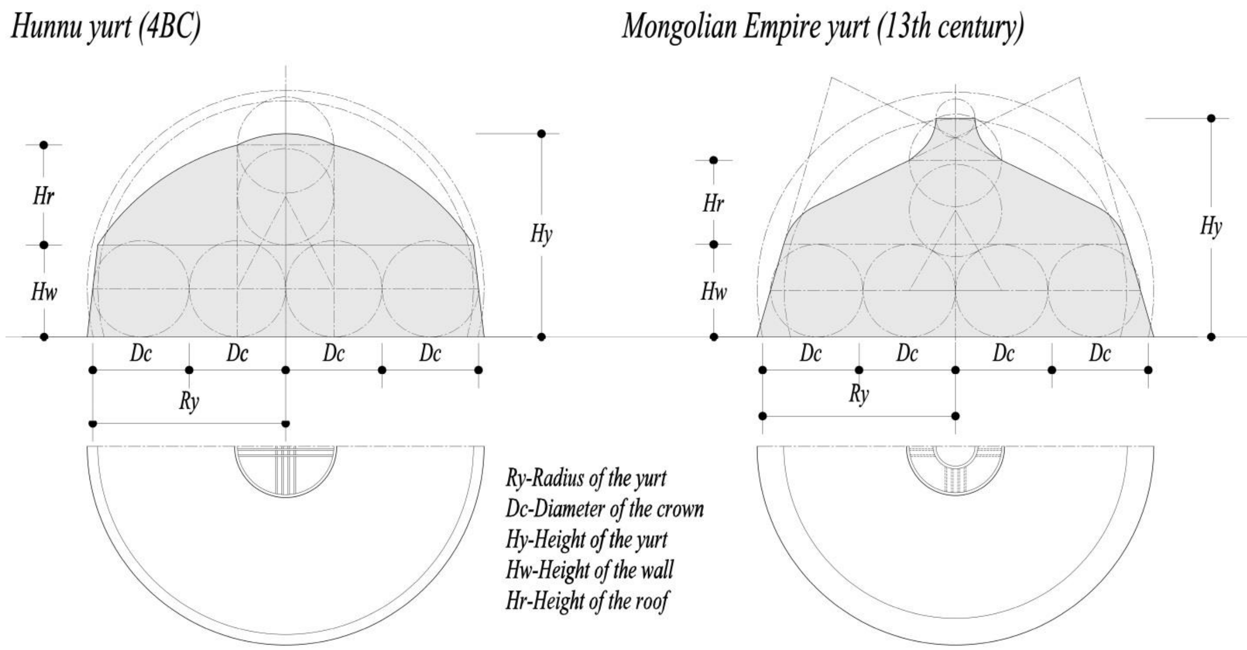

Figure 10: Drawing of Hunnu and Mongolian Empire yurt

<u>*Inner Mongolian Yurt*</u>*:* As illustrated in *Figure 11*, the crown of Inner Mongolian yurt is much bigger than Mongolian yurt. The structure of Inner Mongolian yurt is still kept in contemporary Inner Mongolians cultural and traditional application. The yurt applies wooden trusses (*Figure 7*) in connecting the poles rather than pole holes. And the poles are lightly connected with the sides of the wall [26][28].

<u>*Hungarian Yurt*</u>*:* Hungary is the only country which has its traditional yurt in the continent of Europe. The history of Hungary shows Hungarians used to live in typical roundhouse yurt which is similar to Hunnu yurt as shown in (*Figure 11*) [34].

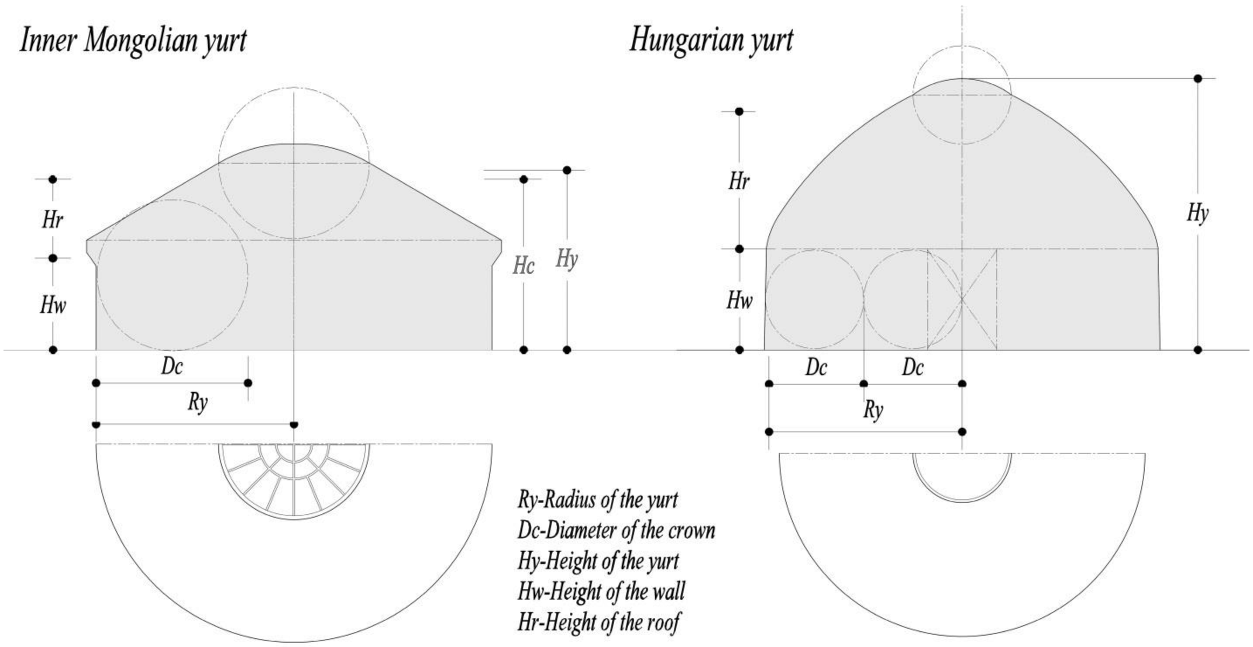

Figure 11: Drawing of Inner Mongolian and Hungarian yurt

Middle East Yurt: In the modern times, a certain number of people in Middle East countries including Kazakhstan, Kyrgyzstan, Turkmenistan, and Uzbekistan live in the yurt which is closer to the Mongolian yurt (*Figure 12*). Regarding the crown, it is similar to Hunnu yurt, as called 'Saraalj' crown (*Figure 7).* However, the pole design is different as the edge is curved. Also, the Kazakh yurt has a taller roof in relation to its longer poles. Alike other Mongolian yurts, they used to apply felt shutter and in modern times which is changed to wooden doors (*Figure 12*). Some settings of Uzbekistan yurt are varied as having double-sided walls, much taller space (*Figure 14*) and woven cloth is used for wall cover [35].

Afghanistan Yurt: Afghanistan yurt differs from the others through its much smaller rounded, but taller designed structure. In conjunction with that, the crown is smaller than the other types (*Figure 13*) [26]. The old version of the Afghan mobile yurt is made of latticework wooden frame, which is covered with woven reed matting bands in several different colors. Several long poles are fastened with special knots, supporting the poles to the wooden frame (crown) on the top. There is usually intricately designed felt which is fixed on the top of the roof, while decoration usually appearing inside of the yurt [35].

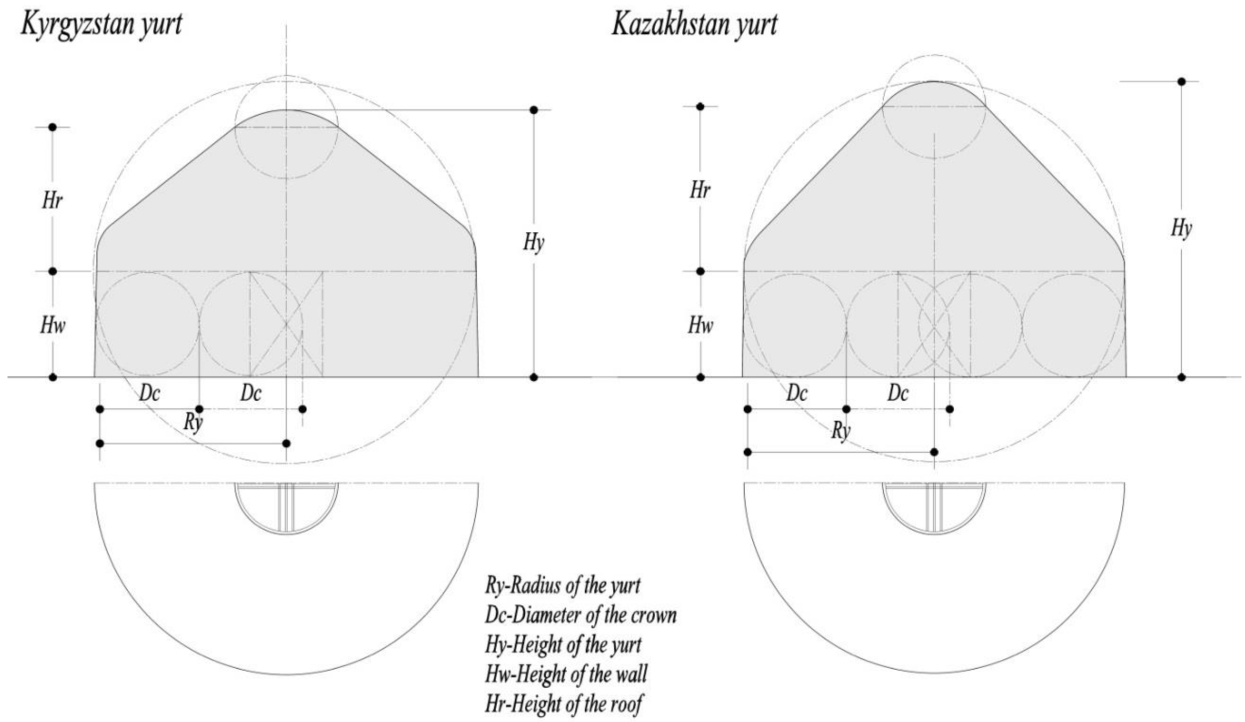

Figure 12: Drawing of the Kyrgyz and Kazakh yurt

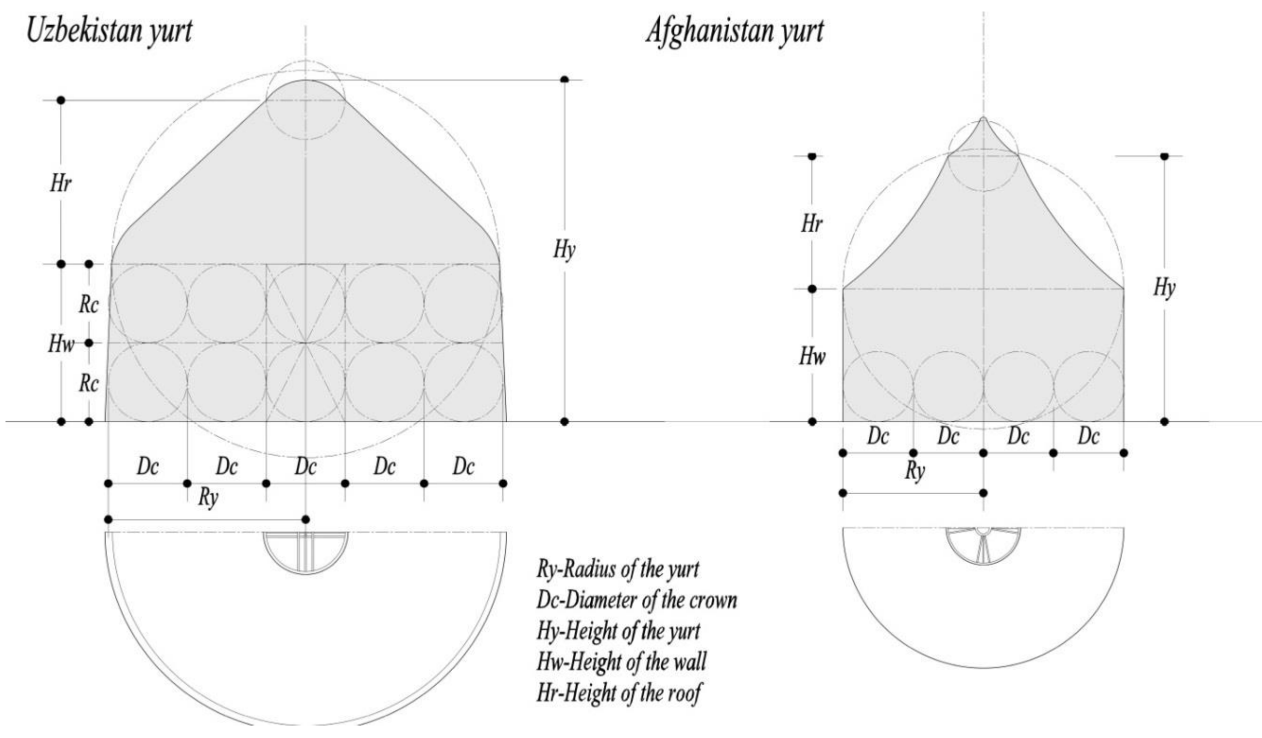

Figure 13: Drawing double walls yurt and Afghanistan yurt

Iran Yurt: In Iran, the yurt is called either 'Chador' or 'Kapar' (*Figure 14*). To adapt the hot as well as humid weather conditions, Iranians does not put crown at the top of the yurt. Folding lattices combined with straps or felt are used to cover walls. To create the roof, they usually use poles or slats, fixed from above into a wooden hoop. In a dome shape, the cylindrical framework of the vertical round wall is attached at the side to the forks of the poles. The interior is decorated with carpet or felt covers on the floor and the door is designed to be either felt cover or light wooden structure [36][37].

American Yurt: The most modernized yurt in the world is the American yurt. As the Americans have designed the yurt structure comparatively recently, the most advanced materials have used for the structure. The yurts are mainly used for tourism for the USA and Canadian context. And to enable better ventilation, Americans have designed windows on the walls, apart from the crown at the top. Steel cables have used to connect the poles. And the yurt has managed to have several separate rooms inside. The general shape and look are similar to Mongolian yurt, but which is constructed with much higher doors and walls (*Figure 14)*[23][38][39].

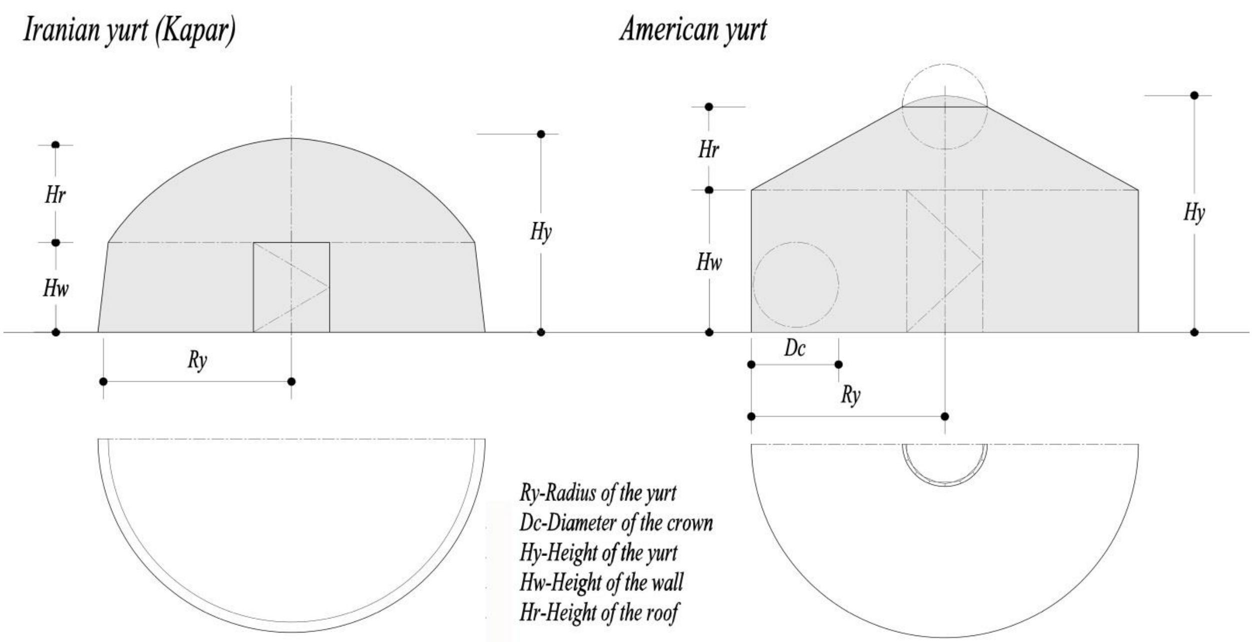

Figure 14: Drawing of the Iranian and American yurt

In *Table 4* all available yurt types are systemized according to place, historical time of usage, functionality, structure and – in addition – temperature values of the climate zones [16].

Dymaxion 'Wichita' House: After the World War II, in 1940Buckminster 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, aluminum and Plexiglas were used. And he calls the house as 'Dymaxion House'. The Dymaxion House shape was identical to the yurt, however, in relation to the materials used for the house, its weight was as much as 2700 kg. And another similarity between the house and yurt was its natural ventilation system which Fuller calls 'dome chilling effect' [40][41]. And 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.

Table 4: Systemized general information of different yurts with additional climate data.

Types of the yurt	Country	Start period of usage	Function	Materials	Crown	Climate /max-min temperatures in ºC/
Hunnu yurt	Mongolia	4th BC	residential	wooden frame, felt cower	Saraalj	30.6-(-22.5)
Mongolian empire yurt	Mongolia	13th century	residential	wooden frame, felt cower	Double Saraalj	30.6-(-22.5)
Mongolian Yurt	Mongolia Buriad Khalimik	1900	residential tourism symbol	wooden frame, felt cower, cotton cover, water protection	Khorol, Saraalj, SarkhinagKhorol with trussed wood	30.6-(-22.5)
Inner Mongolian Yurt	Inner Mongolia	1900	residential tourism	wooden frame, felt cower	Khorol with trussed wood	36.4-(-14.3)
Hungarian yurt	Hungary	7th century	residential tourism	wooden frame, felt cower	Saraalj	34.6-(-12.2)
Kyrgyz yurt	Kyrgyzstan	13th century	residential tourism symbol	wooden frame, felt cower	Saraalj	37.1-(-11.0)
Kazakh yurt	MongoliaKazakhstan Turkmenistan Uzbekistan Tajikistan	13th century	residential tourism	wooden frame, felt cower	Saraalj	37.1-(-11.0)
Double wall yurt	Mongolia Kazakhstan Uzbekistan	13th century	residential tourism	wooden frame, felt cower	Saraalj	37.1-(-11.0)

Types of the yurt	Country	Start period of usage	Function	Materials	Crown	Climate /max-min temperatures in ºC/
Afghan yurt	Afghanistan	13th century	residential tourism	wooden frame, felt cower	Saraalj	37.1-(-11.0)
Iran yurt	Iran	13th century	residential tourism	wooden frame, felt cower	-	43.9-4.9
American yurt	USA, Canada	1967	residential tourism	wooden frame, felt cower, midbrain water protection	American yurt crown	44.9-(-11.0)

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 the effects of wind drag on the house. In his wind tunnel analysis, the house was exposed to wind speed from 12-miles an hour (19.3 km/h) to 70-miles an hour (112.6 km/h), from which point the flat planking began to fly off in parallel with the wind direction [40] (*Figure 15*). Rudders that rotated with the wind was the new design innovation implemented by Fuller. The induced vertical-driven vortex sucks cooler air downward if properly ventilated [40][41]. A tornado once passed 270 meters from the 'Wichita house' in 1964, and was not able to cause considerable damage to the structure. The Dymaxion House house never went into mass-production but Fuller's experiment with the wind was a remarkable success [40].

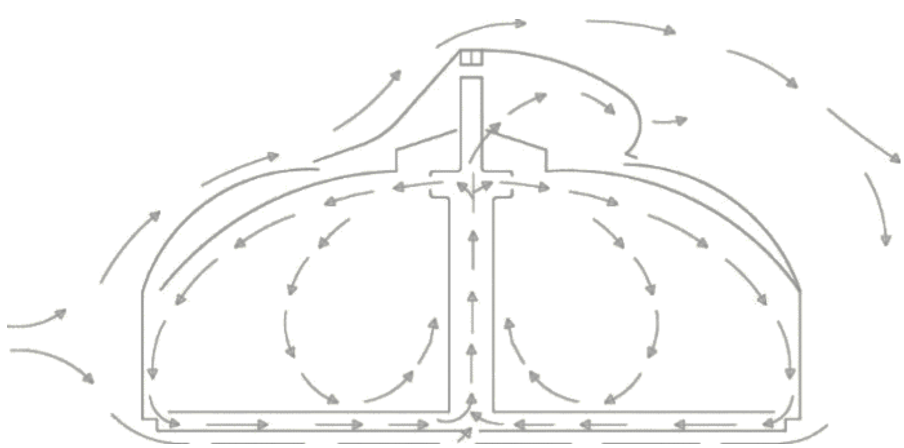

Figure 15: Dymaxion Deployment unit (Wichita house) [40].

2.5. Conclusions

The yurt is one of the most typical nomadic traditional vernacular architecture solutions. In relation to the modern urbanization, the nomadic culture and yurt living has decreased. One exception is Mongolia that all over the territory there still exists yurt living parts, including the capital city. In the capital city, the yurt living area is called 'Ger area' and in some 'ger areas,' the infrastructure is less developed where the water supply, wastewater treatment system and heating supply systems are not connected. 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 no research has found on building physics performance of yurt neither in professional nor in scientific publications. The most discussed type of yurts in literature is Mongolian, Kazakh, and Kyrgyz yurts from its architectural and structural characteristics, and which lacks climate and energy issues. Therefore there is the need of 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.

3. CLIMATE DESIGN FOR THE TRANSPORTABLE RESIDENTIAL BUILDING IN THE COOL CLIMATE ZONE

3.1. Building shape

Building shape is regarded as the overall form of the building including building plan, its size, and heights [42]. Depending on the shape, the two geometric characteristics of the floor area and surface area are set and which have essential mean for the building energy efficiency [42].

Floor area: The floor area of the building has a direct relationship with the material for the structure and energy use. Because the large buildings needed more structure materials and also the more energy needed for the heating, cooling, ventilation and other energy loads [42].

Surface area: The surface area follows the shapes of the building and façade exterior designs. Surface area is one of the critical characteristics of the building energy efficiency. In the winter season, massive heat is lost from the building surface area, inversely it has the potential to gain heat from the sun radiation. In the summer season, surface area gains excessive heat into the building, hence the cooling function is more demanded.

The heat loss in regards building energy consumption is calculated by the following heat transfer equation.

Heat loos= $(A/R)*(T_{indoor} - T_{outdoor})$

A- The surface area of the building

R- Thermal resistance (R-Value)

T_{indoor} – Indoor temperature

$T_{outdoor}$ - Outdoor temperature

To compare the different shapes of the building, the area ratio is calculated by comparing the surface area to floor area. Smaller the area ratio indicates lesser the energy consumption for heating and cooling in terms of per unit of floor area in the building [42].

Area ratio= Surface area / Floor are (Figure 16) [42].

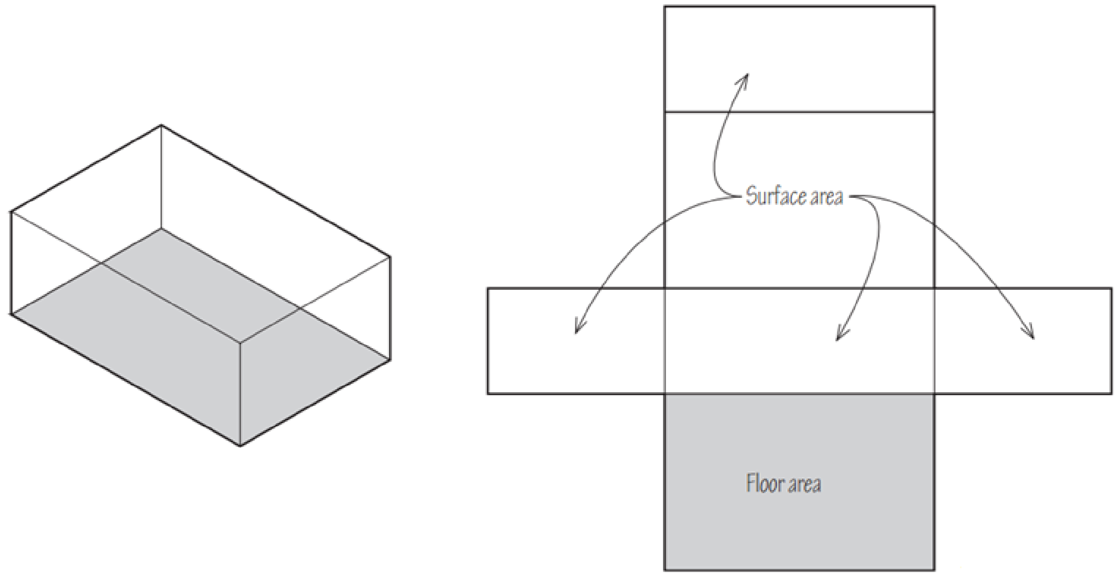

Figure 16: Building floor area and surface are [42].

Comparing single floor buildings with different shapes of rectangular, square, pentagonal, and circular and set the height of building and floor areas as same, the area ratio provides -1.68 for rectangular, -1.64 for square, -1.61 for pentagonal and -1.57 for circular shape buildings [42]. Considering the result circular shape buildings, more specifically half globe shape shows the most energy efficient form [42]. In *Table 5* systemized optimal floor areas with the numbers of the stories for the building are shown.

Table 5: Optimal floor areas for the numbers of stories[42].

Floor area (m2)	Optimum numbers of stories
< 93	1
93-465	2
465-929	3
929-2787	4
2787-5574	5
5574-9290	6
9290-13935	7
13935-22297	8

3.2. Outer envelope

In the cool climate zone, the main considerations are minimizing façade heat loss, and enabling solar heat gain for the winter season and for the summer avoiding the thermal gain [16]. The optimal setting in the cool climate zone is suggested to have glazing with triple protection and the glazing percentage should be set for each case with regards orientation; 20-30 cm insulation material is suggested for façade, and the daylight should be sufficiently entered through the skylight if it has set so[16].

Sun protection: Mobile sun protection is suitable for the cool climate because during winter protection from the sun is not required, inversely solar gain is demanded. The east and west façade has the highest radiation incidence in summer, meaning that the sun protection has to block out a low sun [16]. The internal sun protection is best suitable to the south and north façade [16].

Glazing: In the cool climate zone the triple heat protection glazing with a U-value of lower than 0.7W/m^{2}K is ideal[16]. Lower the U-value of glazing decreases the energy cost, as well as the thermal comfort, is enhanced in relation to the increased surface temperature and cold air drop is diminished [43].

Thermal bridge: The concept refers to "penetration of the insulation layer by solid" which reduces thermal resistance (R-Value)[42]. The buildings which apply flexible insulation enable the reduction of the thermal bridge as the material connections are generally overlapped.

Doors: Referring to heat loss, the doors have different force at a certain extent than the windows. Generally, buildings have less number of doors than windows except for special kinds like a hotel with exterior entries. In a comparison of solid doors, insulated doors and windows, the lower heat gain/loss is tied to insulated doors, then for solid doors and the highest through windows [42]

Floor: Referring to a study of 33 energy efficient buildings, 24% of the total heat was lost through the ground, especially floor edges show greatest heat loss as found from the infrared scanning hence the necessity of edge insulation is highlighted [42].

3.3. Indoor environment quality

Indoor air quality

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 *(Figure 17)*. CO_2 adversely effects on human body, imposing headache, decrease in performance, and potentially dizziness as oxygen transfer rate is reduced [44].

Figure 17: Values for indoor CO_2 concentration [44].

Thermal comfort

Thermal comfort parameters are included indoor air temperature (°C), mean radiating temperature (°C), mean air velocity (m/s), and relative humidity (%)[45][46][47][48]. 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 [47][48].

The operative temperature involves the combination of air and surface temperature. The most comfortable operative temperature is between the 20-24°C in the heating period and maximum 23-26°C in the cooling period for the normal residential building [47][49].

Human factor: In addition, personal factors also impact on thermal comfort [48][49]. The metabolic rate for human activity is measured by Met formula (1Met=58.15 W/m^2) [121]. And the metabolic rate is least produced by a human during the sleep (0.8 Met), and the greatest during the running (10 Met) [121]. Clothing is one of the main factors to keep the heat and which is referred to as 'clo'. The clothing insulation is demonstrated in *Figure 18,* expressed as clo unit (1clo=0.155°C/W) [123]. Normal business suit, with cotton underwear, is equivalent to 1 clo. And the 'clo' measured for a short-sleeve shirt to warmest arctic suit ranges between 0.25 and 4.5 [121].

Figure 18: Insulation of clothing with Clo unit [50].

Building factor: The thermal comfort applicable to the building is categorized in line with DIN EN 15251. In 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 6.*

Table 6: comfort categories according to DIN EN 15251[45].

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. 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 7*and *Figure 19*), [45][46].

Table 7: Classification according to DIN EN ISO 7730 and DIN EN 15251[45][46].

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*. To meet the best condition, at least 5 percent of the population needs to be dissatisfied [50][51].

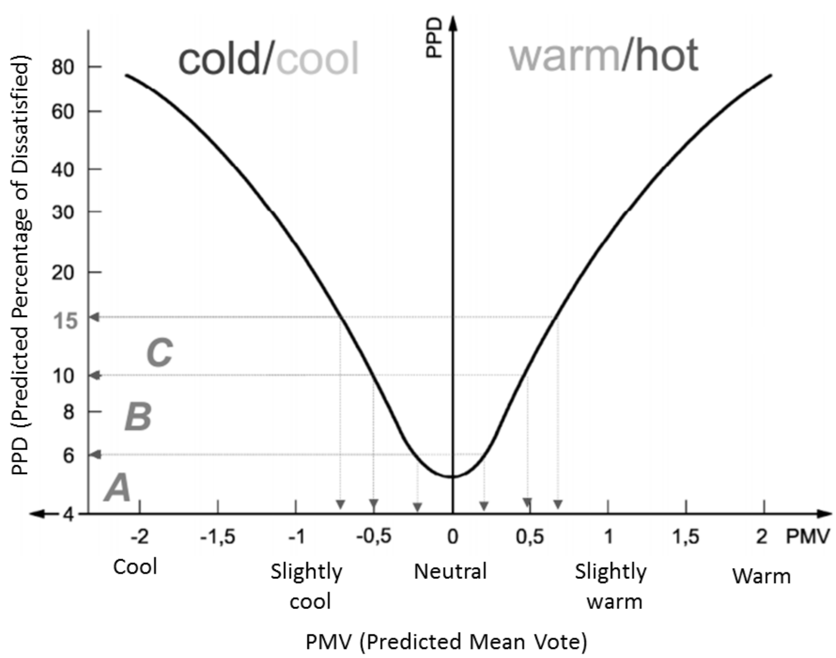

Figure 19: Predicted mean vote (note that at least 5% of any population would be dissatisfied even under the 'best' condition)[50][51]

3.4. System

In the cool temperature climate zone, heating necessity is much greater than cooling where more fresh air complemented with humidity is required [16]. And heat recovery system attached to mechanical ventilation is important to meet comfortableness [16].

Heating

The heating requires a significant amount of energy (about 40 to 60kWh/m^2) and of which 10 percent need to be humidified. The amount of energy consumption can be reduced to 10 kWh/m^2a as if the other functions of the building, including external wall, thermal insulation, heat protection glazing, and heat recovery system attached to mechanical ventilation system are correctly put in place [16]. The renewable heating/ cooling system forms an essential part of suitable system combination and coverage degree. In below Figure, optimal installation position and room conditioning system's heating and cooling performance related annual yield for a solar power system is demonstrated [26].

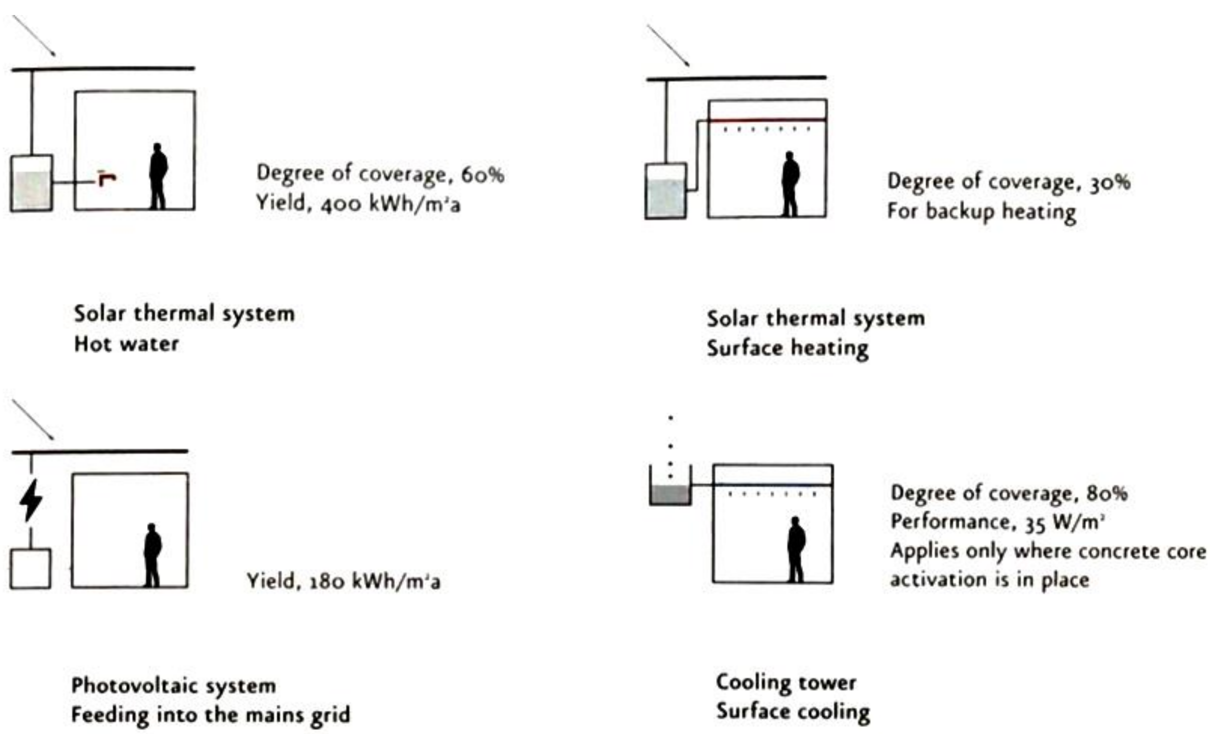

Figure 20: Room conditioning concept in combination with renewable energy generation system dedicated to cool climate [26].

The low percent of glazing and unshaded south façade suits for heating and the heating energy requirement is increased due to façade direction and its window surface [26].

Radiator: In the cool climate zone, simple technology would have been set alike radiator attached natural ventilation as if the comfort was not demanded [26]. For the summer season, the rooms are better to have night ventilation openings. If the air exchange demand is low, the thermal activation of storage masses can be applied. For indoor cooling, mechanical ventilation is useful for certain degree [26].

Cooling: In the absence of an active cooling system, then the moderate glazing percentage solution can be combined with external sun protection, and efficient night cooling to ease the summer room climate.

Ventilation

The ventilation has two main roles for building technology: one is to enable air exchange in light of fresh air and thermal behavior for the building [118]. In consideration of comfort, it is suggested to have mechanical ventilation [26].

Within yurt structure, a top opening and the lower edge of the walls enable natural ventilation which is referred to as 'Dome chilling effect' [40][41]. The air is exchanged very well and for summertime, the cooling effect works well. The cross ventilation is also enabled through the door and lower edges of the walls are opened at the shadow side. In winter time, mechanical ventilation is suitable to avoid unnecessary heat loss through the automated or systemized opening.

3.5. 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 to 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 [52][12[53].

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 [54]. 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.

In below *Figure22*, the map of the wind energy resource of Mongolia is illustrated [54].

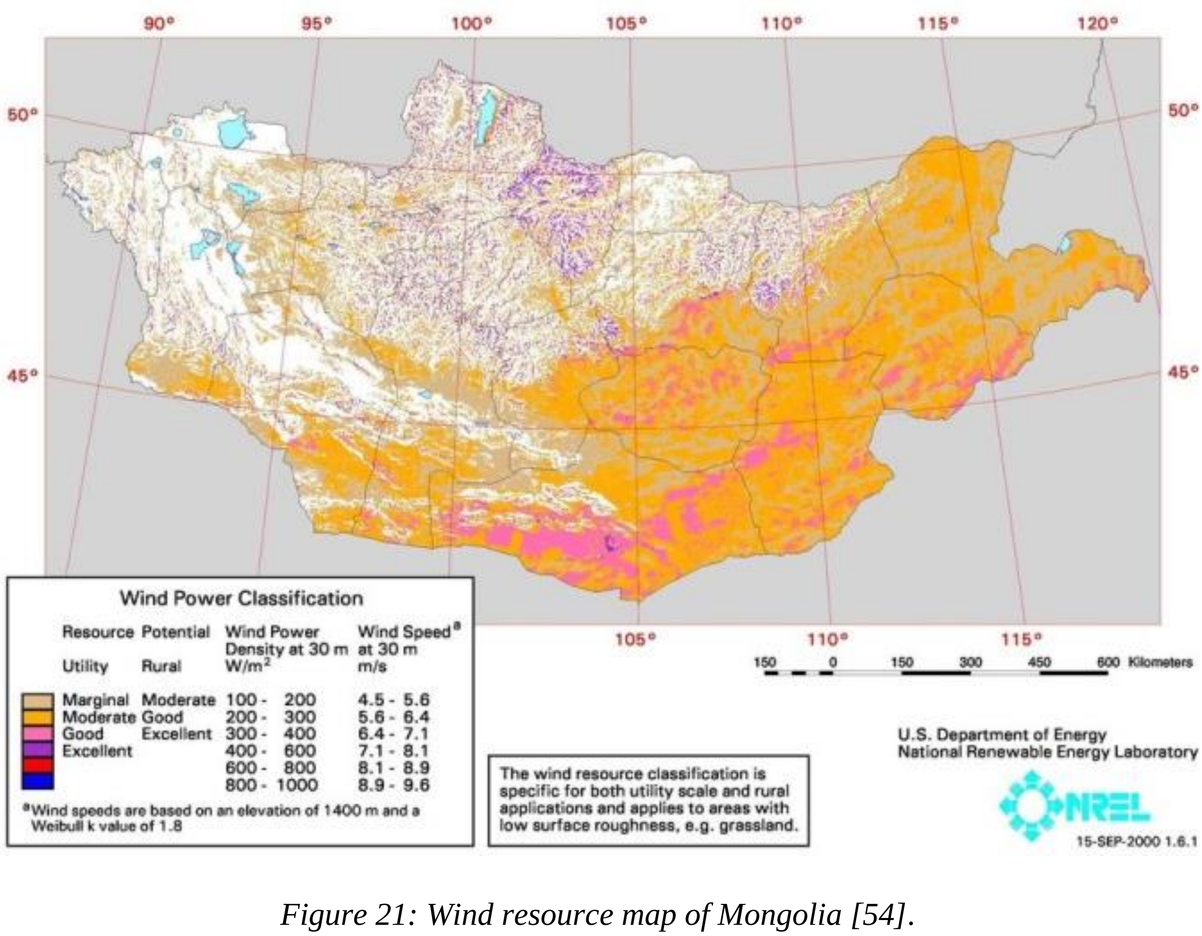

Figure 21: Wind resource map of Mongolia [54].

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 [54][55].

Solar energy

The solar energy source can be used to electricity by the solar photovoltaic (PV) system and to generate heating solar thermal system [42]. It is assumed that a photovoltaic system's yield is about 180KW/m^2a in the ideal installation condition [16].

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 sunshine per year [129,131]. 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 sunshine per year [54][52]. Solar energy is a suitable source for rural areas [54]. Today the herdsman households use mobile solar PV system for lighting, television, and dish for the television, radio, freezer, and fridge [54]. 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 23* 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 [56]. However, for heating in Mongolian cool climate season, merely thermal solar system is not sufficient and which is required to be complemented by other heating sources [16][54][56].

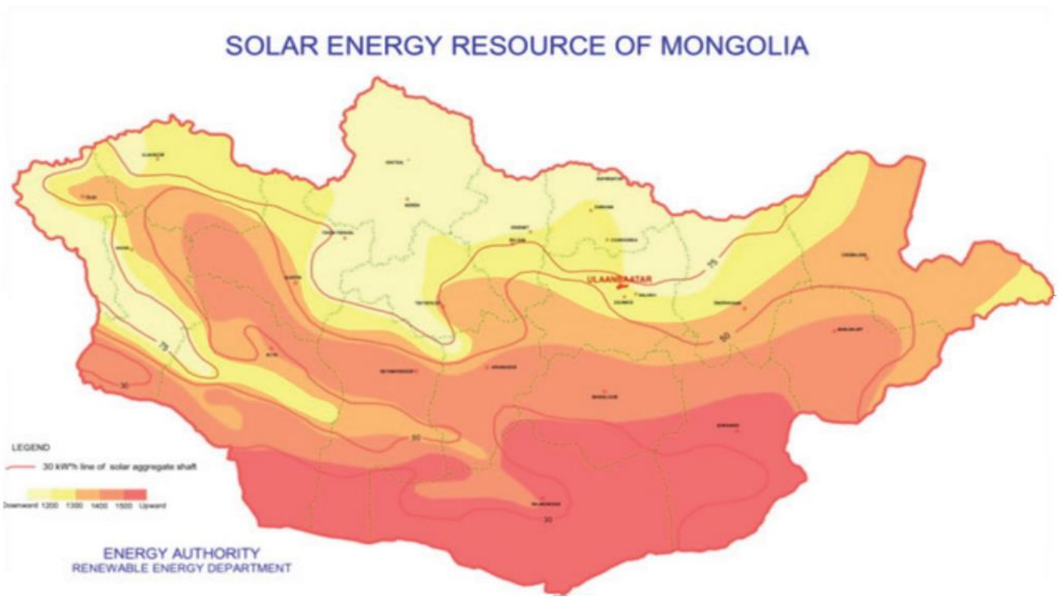

Figure 22: Solar energy resource of Mongolia [54].

The recent progress in solar energy technology provide the opportunity for herdsman households to support its energy demand. The solar panels which are flexible and lightweight forms are suitable as it should meet transportable [57]. In below Figure, the example of a flexible solar panel is shown which is supported by the waterproof material [57]. 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° and the panel is rollable linked to its flexibility [134]. *Figure 24* illustrated examples of flexible solar cells.

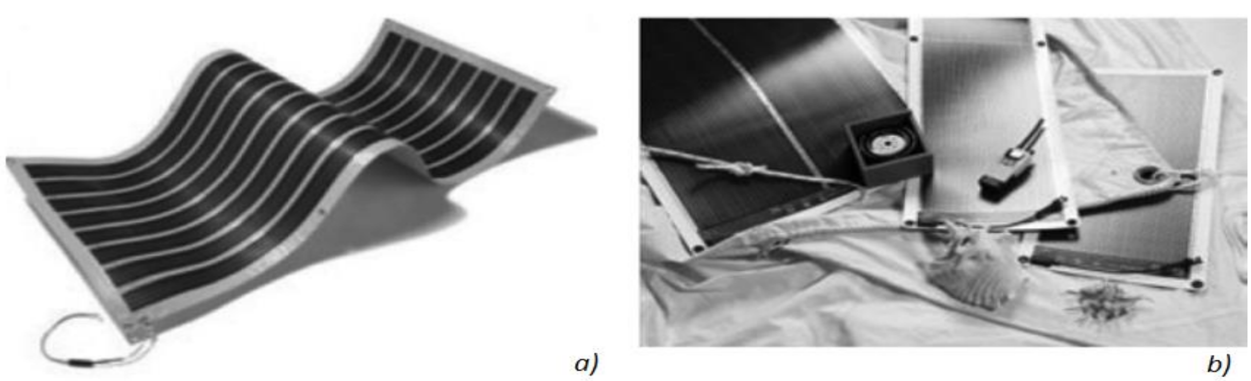

Figure 23: Flexible solar cells, a) Entirely organic b) Using amorphous Si (photo courtesy: Flex cell) Bought are lite weight (25-50 g/m^2), and ideally suited for customized integrate solutions [57].

4. COMPARATIVE ANALYSIS FOR TRADITIONAL YURTS USING THERMAL DYNAMIC SIMULATION

4.1. 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[10][26]. 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 [16]. 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.

4.2. Modeling process of traditional yurts

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 [21]. 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 24*, *Figure 25*, and *Figure 26*.

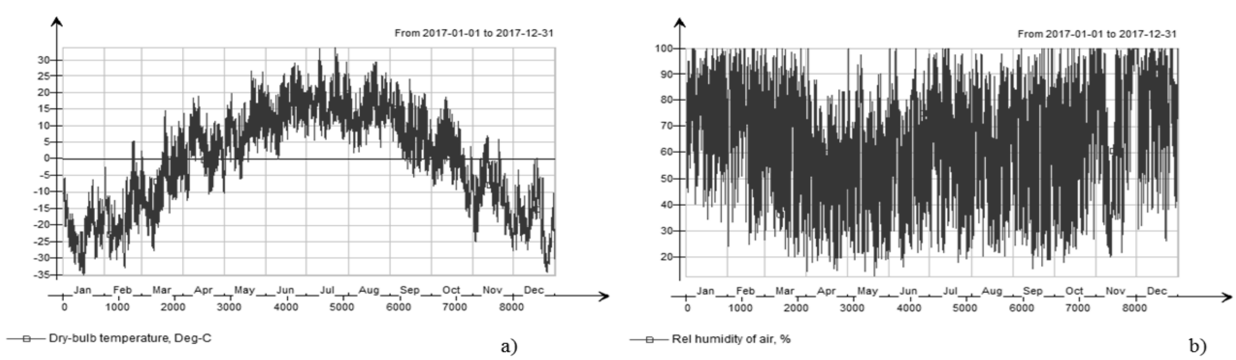

Figure 24: Climate data of Tosontsengel climate station from the 'Meteonorm 7' climate databank, a) Dry bulb air temperature [°C], (8760 hours), b) Relative humidity of air [%], (8760 hours).

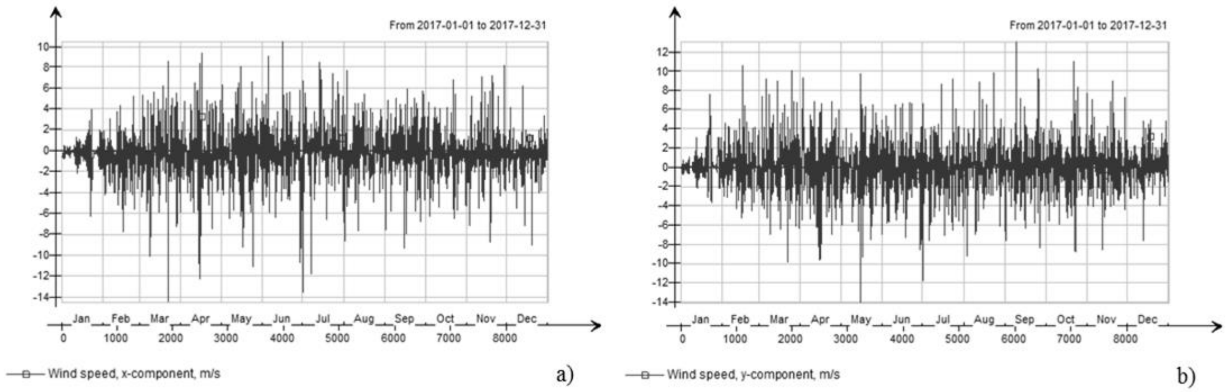

Figure 25: Climate data of Tosontsengel climate station from the 'Meteonorm 7' climate databank, a) Wind speed, x-component, [m/s], (8760 hours), b) Wind speed, y-component, [m/s], (8760 hours).

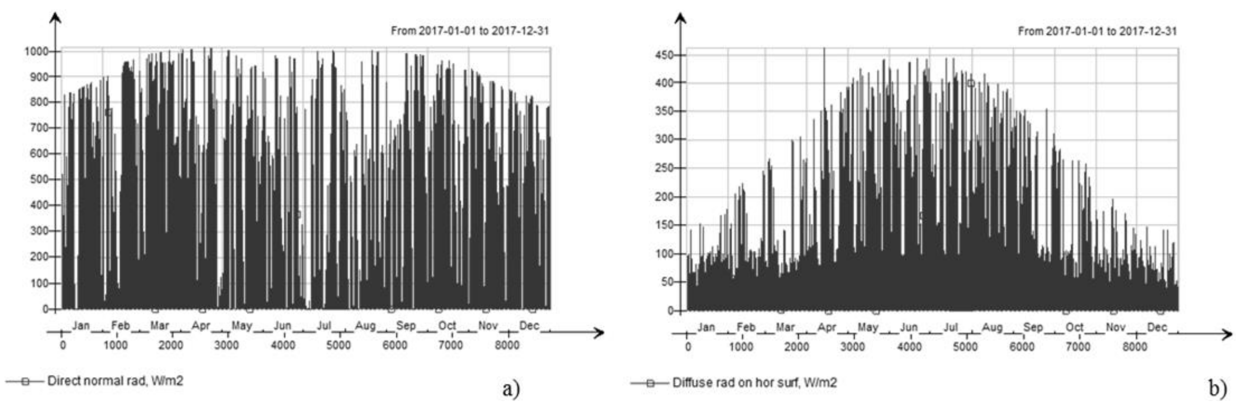

Figure 26: Climate data of Tosontsengel climate station from the 'Meteonorm 7' climate databank, a) Direct normal radiation, [W/m^2], (8760 hours), b) Diffuse radiation on horizontal surface, [W/m^2], (8760 hours).

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[22]. for this simulation. The nine differently shaped yurts gathered from existing and historical practice [10][26]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 (*Figure 27*).

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[58]. 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) [10] of traditional yurts are shown in *Table 8*. The 13^{th}-century Mongolian yurt shows the best results in the comparison, but the Mongolian yurt has shown the closest result to 13^{th}-century Mongolian yurt *(Figure 27).* 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.

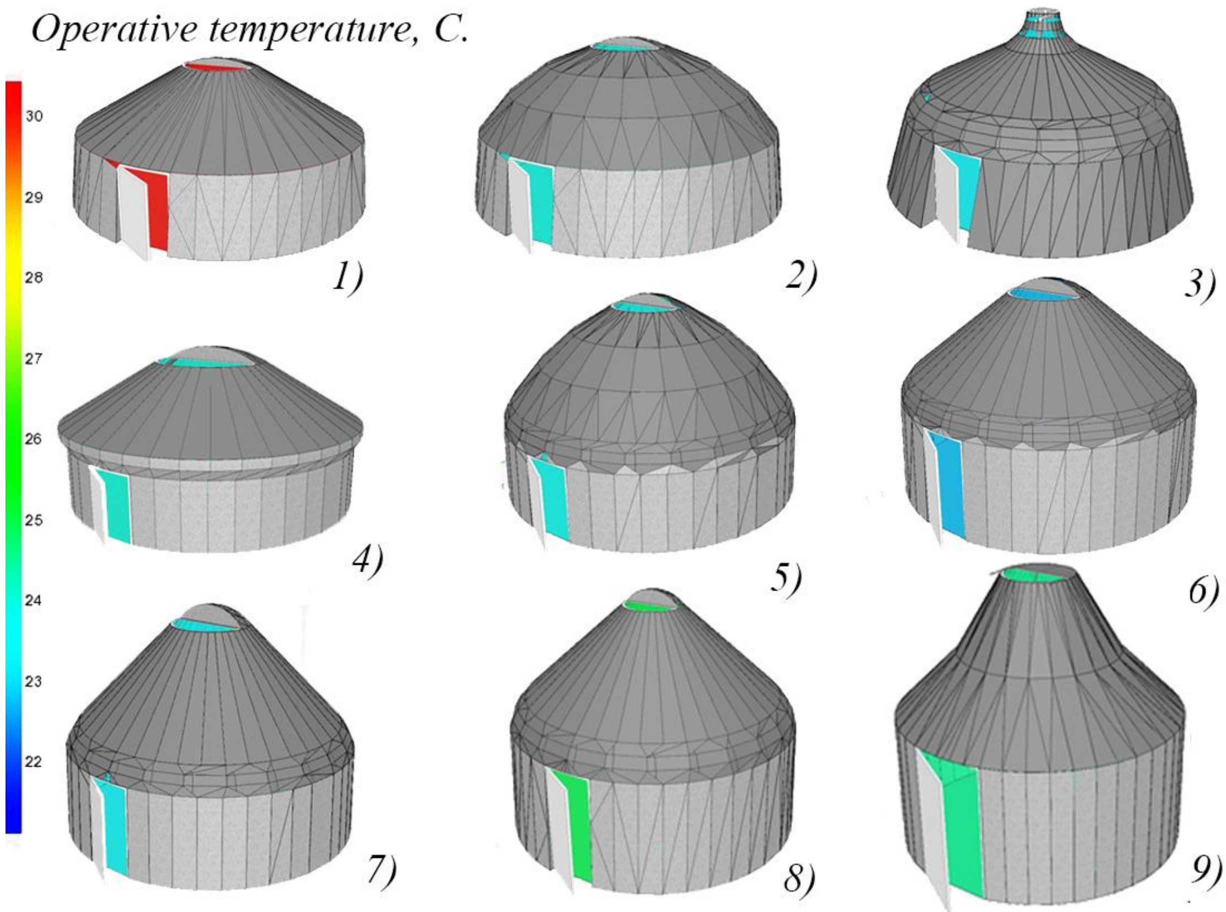

Figure 27: Dynamic thermal simulation models of different types of traditional yurts with indicated operative temperatures. 1) Mongolian yurt, 2) 13^{th}-century Mongolian yurt, 3) Hunnu yurt, 4) Inner Mongolian yurt, 5) Hungarian yurt, 6) Kazakh yurt, 7) Kyrgyz yurt, 8) Double wall yurt, 9) Afghanistan yurt [1],[2].

The more detailed comparative analysis on 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) of traditional yurts are shown in *Table 7*. 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 28).* The best outcomes from each of the parameter are highlighted in grey as shown in *Table8*. 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.

Table 8: 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

4.3. Simulation result evaluation

In this section, system energy delivered energy and energy balance of the nine yurts will be comparatively analyzed on the basis of thermal dynamic simulations.

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 28* and *Figure 29*, 13th-century Mongolian yurt shows the best result in system energy.

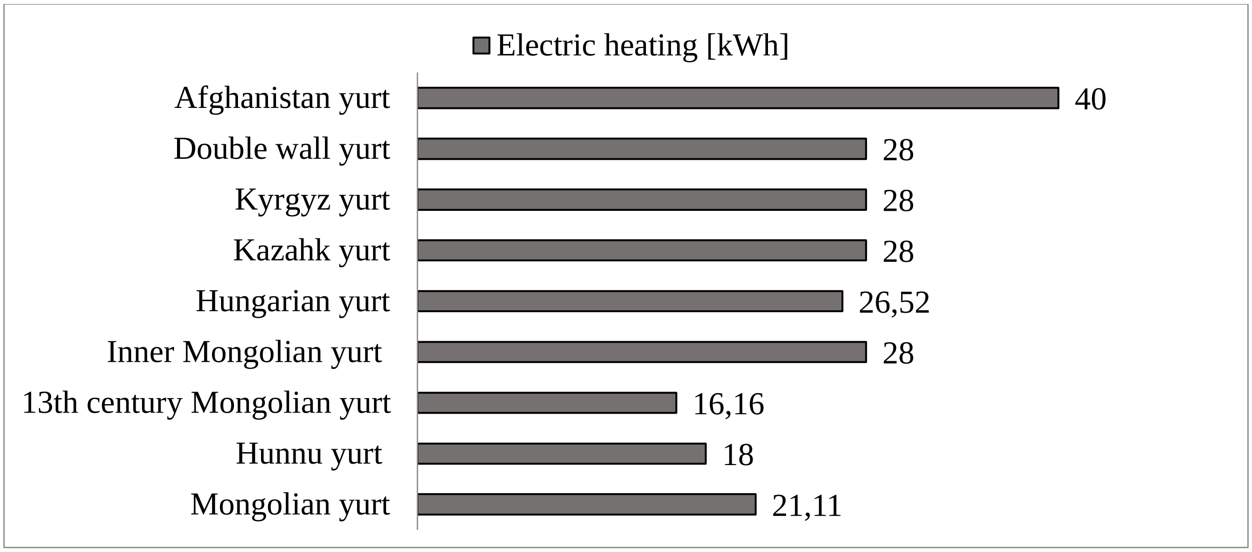

Figure 28: Eclectic heating in system energy of traditional yurts

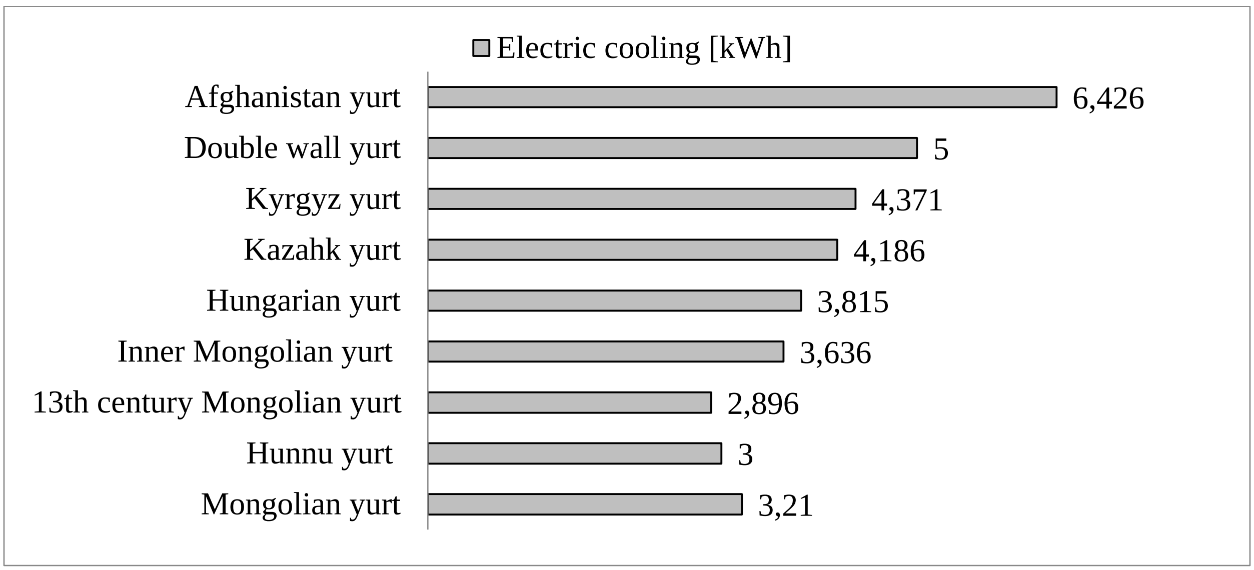

Figure 29: Electric cooling in system energy of traditional yurts

The delivered (purchased) energy of traditional yurts is shown; also the best energy consumption which is the best results for heating (*Figure 30*) and cooling (*Figure 31*) energy were performed in 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.

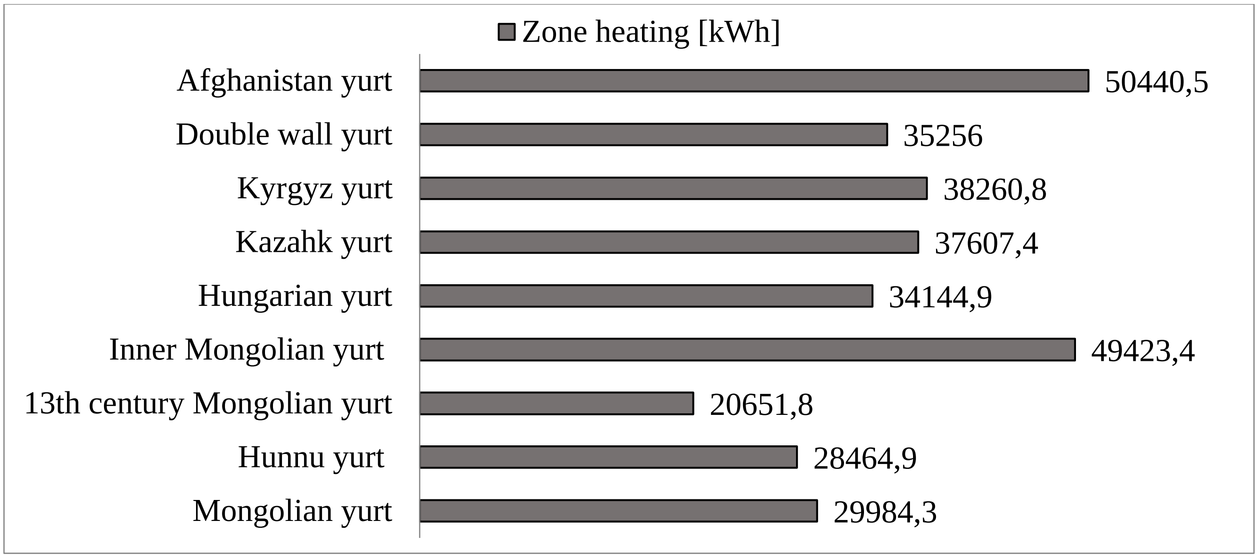

Figure30: Zone heating in the delivered energy of traditional yurt

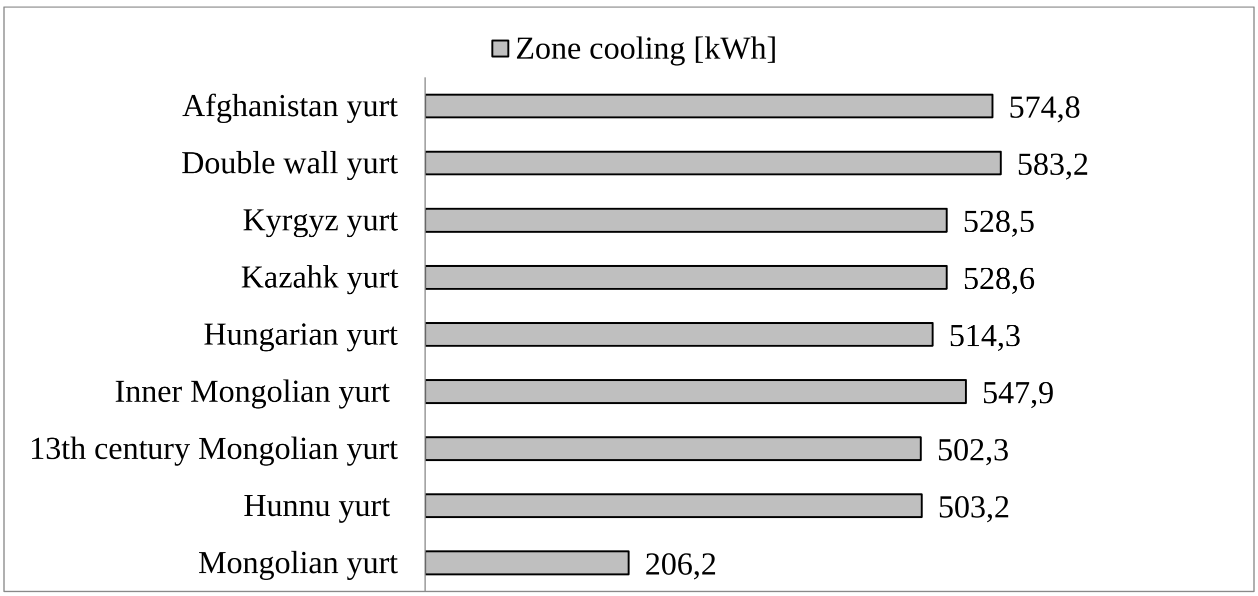

Figure31: Zone cooling in the delivered energy of traditional yurt

As illustrated in *Table9* 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 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 biggest envelope area.

Table 9: The energy balance of traditional yurt

	Envelope & Thermal bridges, kWh	Internal Walls and Masses, kWh	Window & Solar, kWh	Infiltration & Openings, kWh	Total heat loss %
Mongolian yurt					
During heating	-19533.3	-356.1	-833.9	-11180.6	59.0
During cooling	-38	15.5	49.3	-21.3	
Rest of time	-101.3	6.8	9.5	-41.1	
13th-century Mongolian yurt					
During heating	-18658.3	-298.3	-406.7	-5797.2	46.6
During cooling	-30	9.9	22	-8.3	
Rest of time	-102.3	1.5	5.3	-18.3	
Hunnu yurt					
During heating	-19658.3	-356.7	-826.9	-11663.9	60.9
During cooling	-267.6	21	56.6	-41.6	
Rest of time	-267.6	21	56.6	-41.6	
Inner Mongolian yurt					
During heating	-23505.6	-489.7	-1886.9	-27483.3	99.1
During cooling	-248	42.7	117.3	-58.8	
Rest of time	-219.7	4.9	18	-70	
Hungarian yurt					
During heating	-22283.3	-383.6	-866.1	-13930.6	69.8
During cooling	-198.9	23.2	58.7	-44.9	
Rest of time	-225.8	0.5	7.8	-53.7	
Kyrgyz yurt					
During heating	-24105.6	-480	-1063.9	-16605.6	78.6
During cooling	-182.8	27.7	67.9	-44.6	
Rest of time	-182.8	27.7	67.9	-44.6	
Kazakh yurt					
During heating	-23327.8	-453.3	-1040.6	-16780.6	77.4
During cooling	-180.6	26.9	65.9	-46.9	
Rest of time	-180.6	26.9	65.9	-46.9	
Double wall yurt					
During heating	-24891.7	-485	-755.8	-13111.1	73.0
During cooling	-139.4	21.1	44.8	-40.1	
Rest of time	-139.4	21.1	44.8	-40.1	
Afghanistan yurt					
During heating	-27627.8	-928.3	-1492.5	-23958.3	100
During cooling	-116.8	41.6	83.7	-49.2	
Rest of time	-116.8	41.6	83.7	-49.2	

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 32* and *Figure 33*13^{th} century Mongolian yurt and Afghanistan yurt' CO_2level 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[59]. Afghanistan yurt's higher volume effects as well the CO_2-levels.

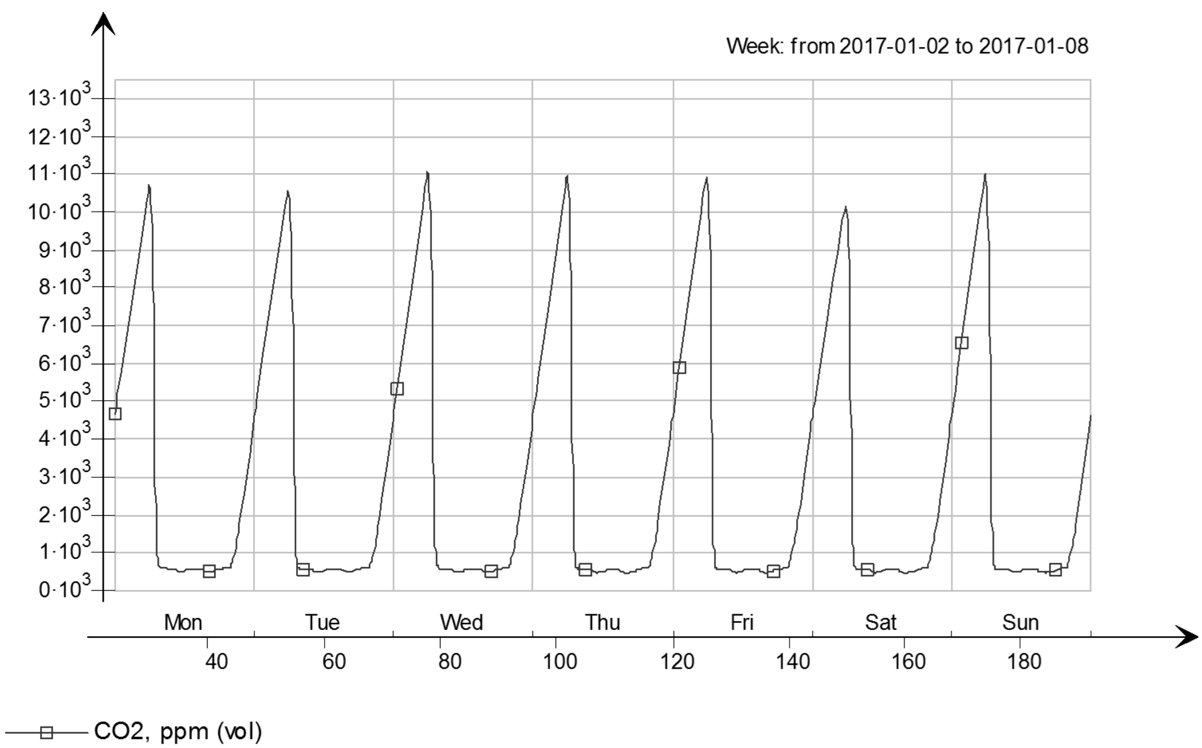

Figure 32: CO_2, ppm of the 13^{th}-century Mongolian yurt (8760h)

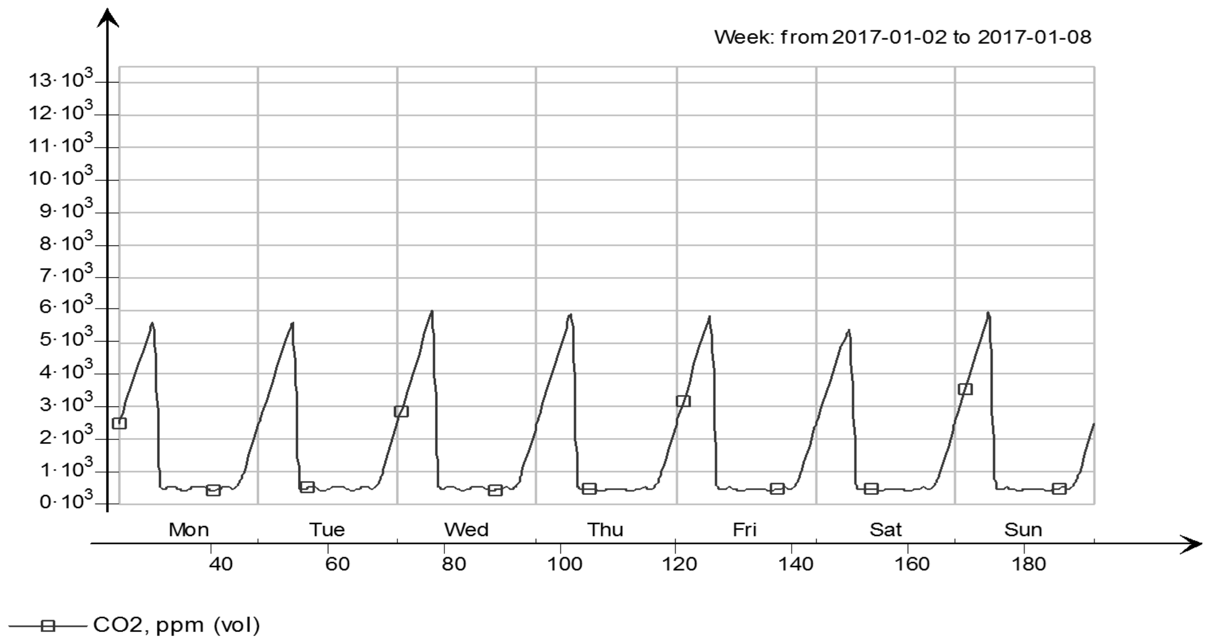

Figure33: CO_2, ppm of Afghanistan yurt (8760 h)

Thermal comfort according to EN 15251[119]: *Figure 34* 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.

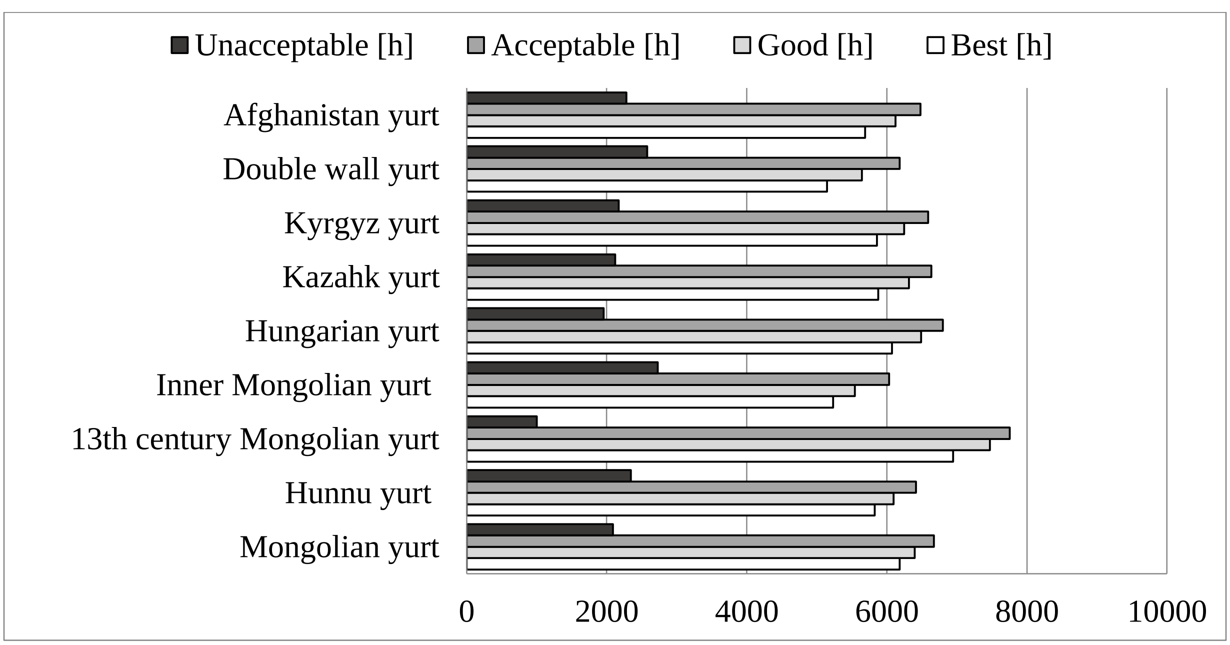

Figure34: Thermal comfort category and numbers of occupancy hours.

The comparative result on the PMV (Predicted Mean Vote) is shown in *Figure 36 and Figure 37* the best-resulted yurt is the Hunnu yurt (*Figure 35*), 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 [46]. Afghanistan yurt (*Figure 36*) 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.

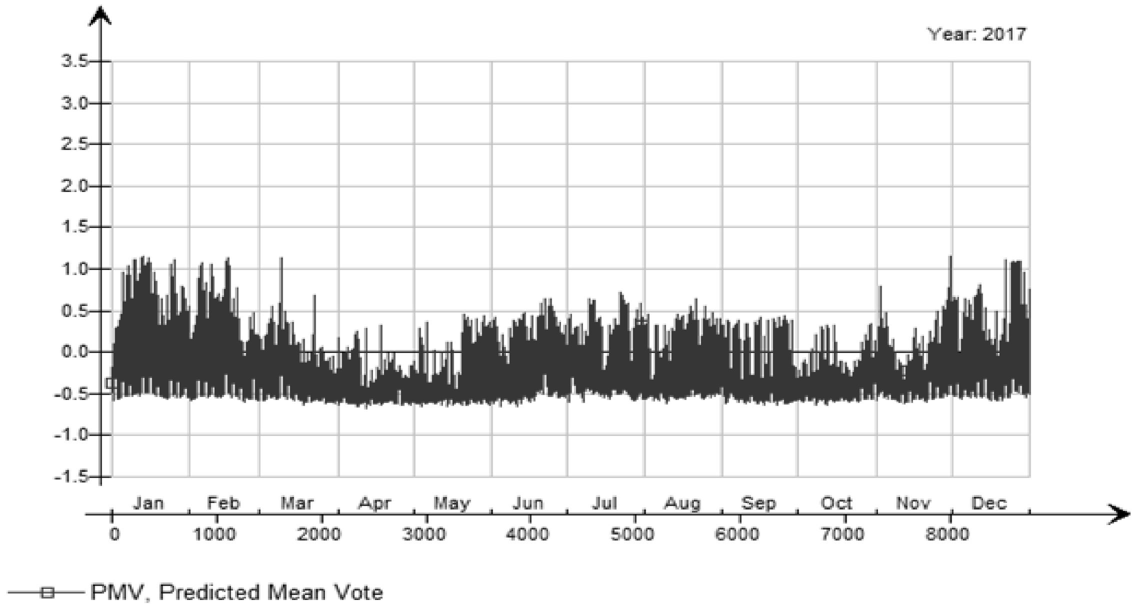

Figure35: PMV, (Predicted Mean Vote) of 13th-century Mongolian yurt, (8760 h)

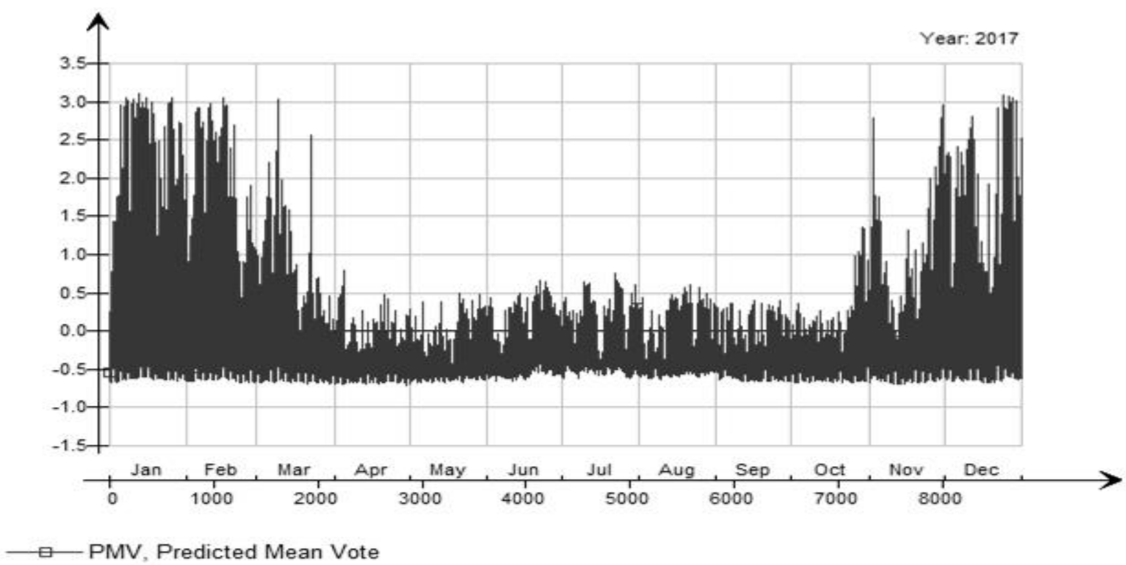

Figure 36: PMV, (Predicted Mean Vote) of Afghanistan yurt, (8760 h)

4.4. 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.

5. DEVELOPMENT OF THE MOST EFFICIENT VERNACULAR YURT VERSION

5.1. The methodology of the study

The aim of this chapter is to develop a modern vernacular transportable residential building. 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 the modern yurt. The type of yurt selected as the base for upcoming research has found to be the 13th-century Mongolian yurt (as discussed in Chapter 4) in terms of its thermal dynamics processed from IDA-ICE 4.8 simulation. The key components considered for development are opening, orientation, structural material, and system. Following steps have been conducted:

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

5.2. Investigated components of the study

5.2.1. 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. And at last, the door is insulated by new material which is tested for heat loss.

Top opening: The top opening works as a skylight and which is the main part of the ventilation of yurt [1], [2]. Top opening has one of the biggest heat loss elements of the yurt which reaches 10.7% to 50.9% heat loss from the simulation result of traditional yurts' examination. In below *Figure 37,* 3 different types' yurts are illustrated. However, there are 5 different types of top openings in relation to the differences in glazing.

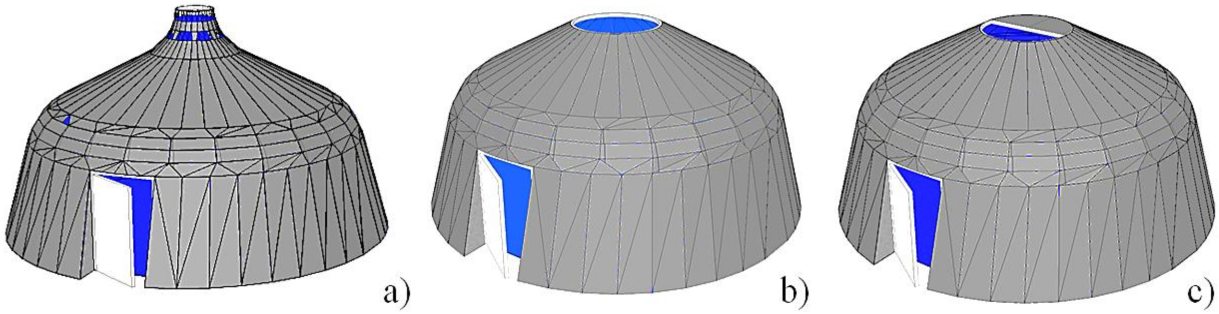

Figure 37: Different types of yurt top opening, a) OP-01, OP-02, b) OP-03, OP-05, c) OP-4.

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 10*, the detailed information on top openings has illustrated in terms of systemized opening types, diameter, area, and glazing types (*Figure 37*).

Table10: Detailed information of 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

<u>*System energy*</u>

In below *Table 11*, the best result of yurts in terms of system energy is highlighted in grey. The OP-3 shows the best result in total as it has a bigger top opening which supports the heating through solar gain. During the cooling period (summer) small top opening provides better results.

Table11: Comparison of the system energy in top opening types

Meter	OP-01 Total, kWh	OP-02 Total, kWh	OP-03 Total, kWh	OP-04 Total, kWh	OP-05 Total, kWh
Electric heating	9542,6	10556,7	7451,7	7851,8	8129,1
Electric cooling	318,2	305,5	1209,2	1049,4	1245
Total	9860,8	10862.2	7451,7	8901,2	9374,1

Delivered energy: In below *Table 12,* delivered energy of the top openings are demonstrated and from which the best results are highlighted in grey.

The OP-3 is best resulted, during the heating and OP-02 is best resulted for a cooling period. In terms of lighting facility and equipment &tenant, all types of OP show same results.

Table 12: Comparison of the delivered energy in top opening types of the yurt

Meter	OP-01 Total, kWh	OP-02 Total, kWh	OP-03 Total, kWh	OP-04 Total, kWh	OP-05 Total, kWh
Lighting, facility	306,5	306,4	306,4	306,4	306,4
Electric cooling	159,1	152,7	604,5	524,7	622,5
Electric heating	9542,6	10556,7	7451,7	7851,8	8129,1
Equipment, tenant	3153,3	3153,3	3153,3	3153,3	3153,3
Total	13161,5	14169,1	11515,9	11836,2	12211,3

Heat loss and gain: In below *Figure38*, 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.

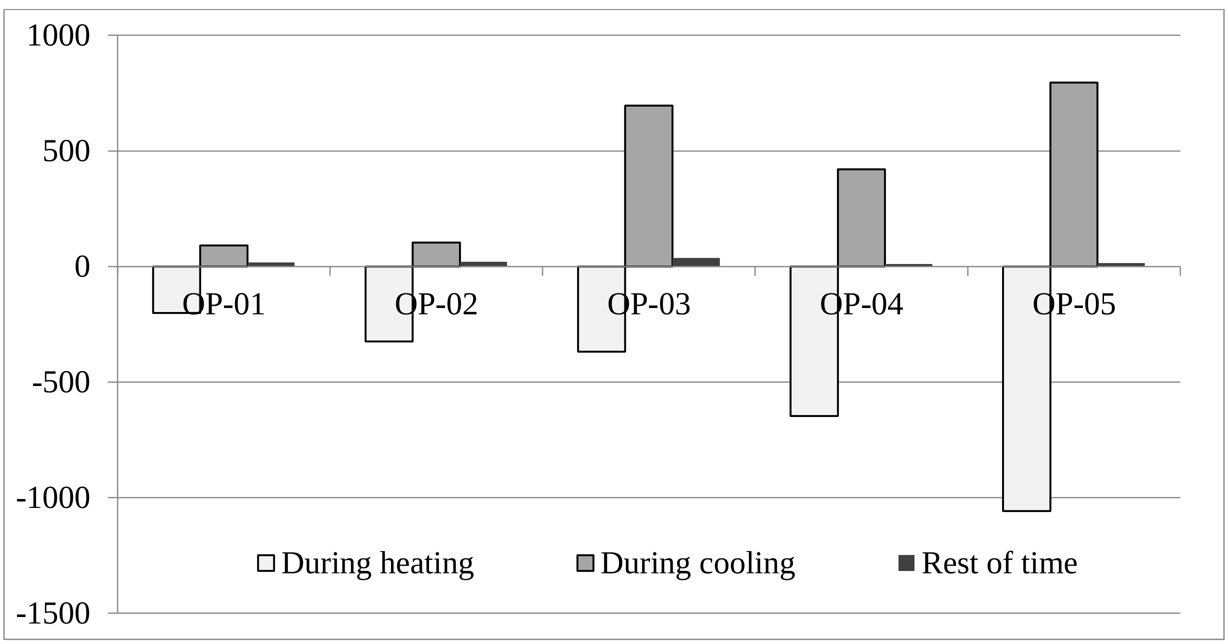

Figure38: Heat loss and heat gain of the top opening for the yurt.

Thermal comfort: All types of top opening with glazing show same results in terms of thermal comfort with occupancy hour setting as illustrated in below *Figure 39.*

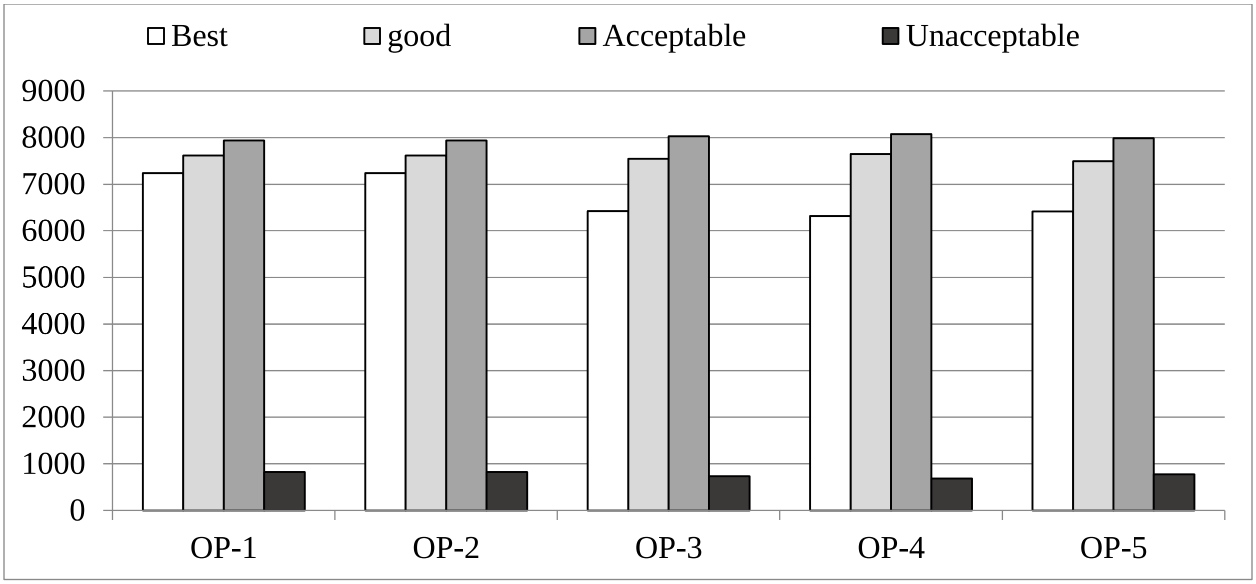

Figure 39: Thermal comfort comparison for the top opening of the yurt with numbers of occupancy hours.

<u>*Daylight*</u>*:* For the daylight factor only two types of top opening have considered for further examination as the 5 top-openings have 2 different glazing. Below *Figure 41, 42* illustrates the daylighting of the two top-openings: 1) the small top opening (see. *Figure 37- a*) and 2) bigger top opening *(*see *Figure 40)*. Small top opening daylighting result shows less than 1000 Lux (*Figure 41*) and the bigger top opening daylighting result shows 0 to 9000 Lux in *Figure 41*.

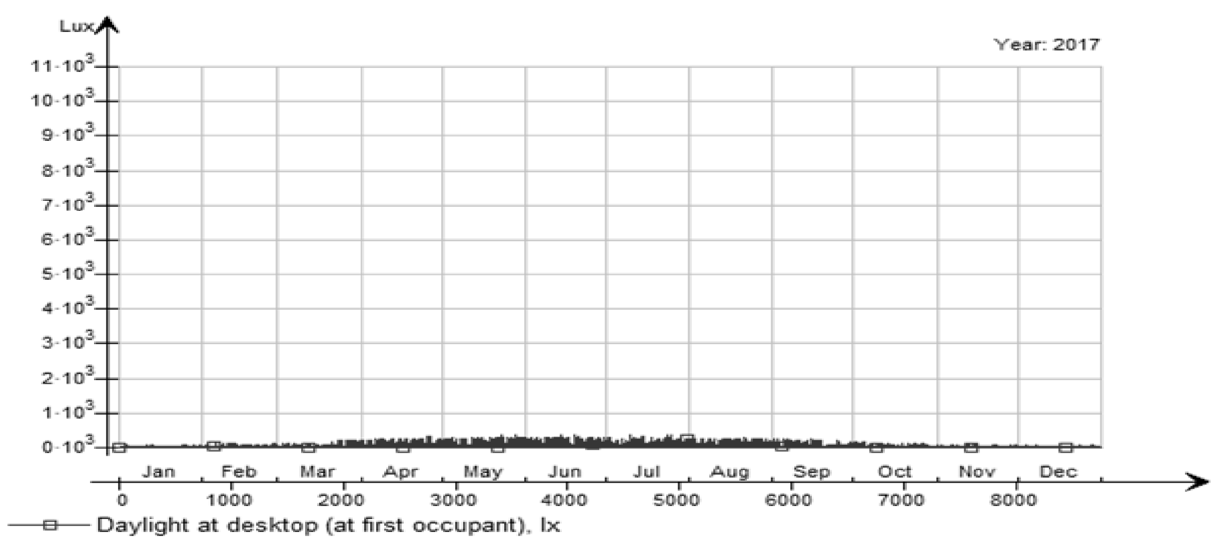

Figure 40: Daylighting at the desktop of OP-2 (8760 h)

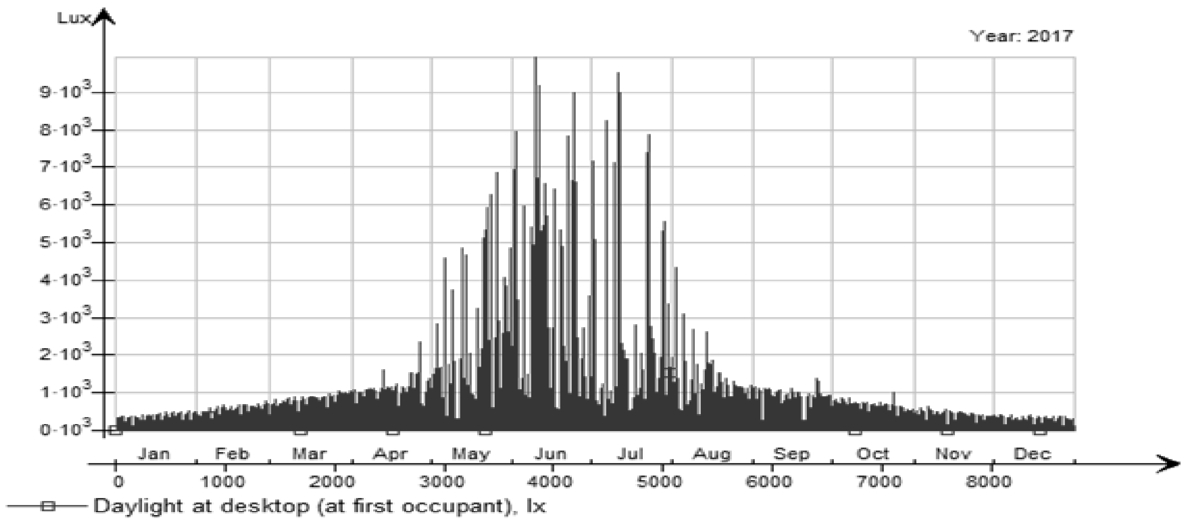

Figure 41: Daylighting at the desktop of OP-5 (8760 h)

<u>*Window:*</u> 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% [26]. For the window development, the OP-3opening type has selected as a base for window development as which has shown best result in thermal analyses. And 6 different type of windows is designed for simulation which is numbered as OP-6 to OP-11 as illustrated in below *Figure 42.*

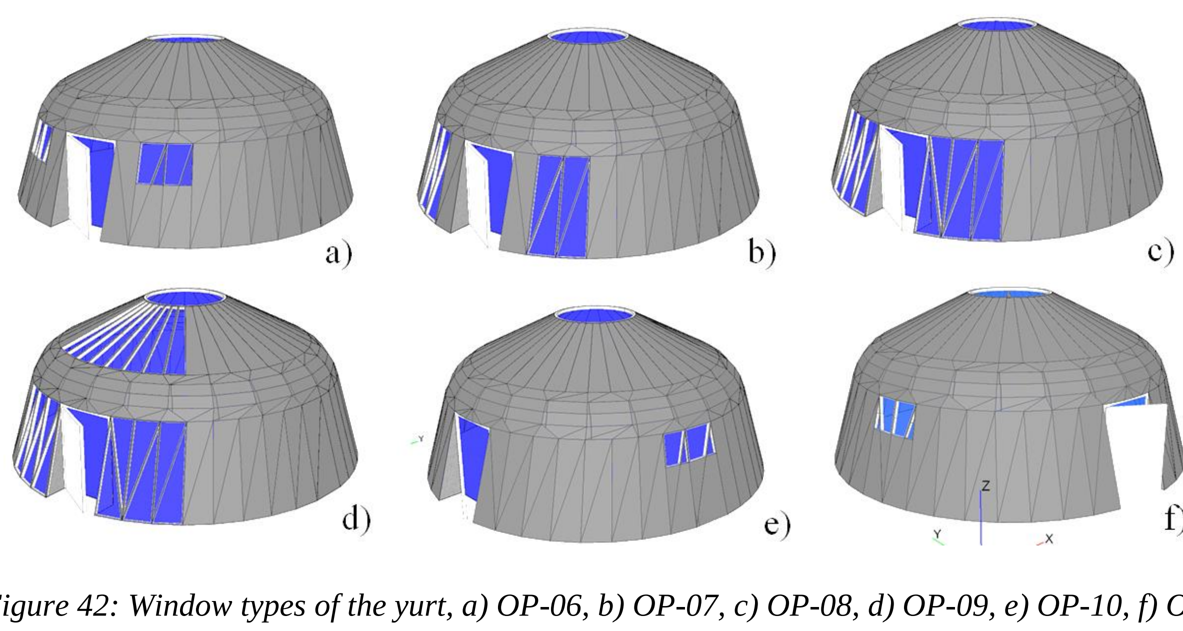

Figure 42: Window types of the yurt, a) OP-06, b) OP-07, c) OP-08, d) OP-09, e) OP-10, f) OP-11.

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

Table 13: Types of the window for the yurt

Opening type	Elevation side	Area, m²	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

Windows system energy comparison: In below *Table 14*, the best results of system energy are highlighted in grey. From the result, OP-11 shows the best result for all categories.

Table 14: The system energy comparison in types of the window

	OP-06 kWh	OP-07 kWh	OP-08 kWh	OP-09 kWh	OP-10 kWh	OP-11 kWh
heating	7412,4	7372	7388,1	7567,8	7541,6	7516,7
cooling	1394,6	1726,7	2011,4	2999,8	1282,8	1277,7
Total	8807	9098,7	9399,5	10567,6	8824,4	8794,4

Delivered energy comparison: The results from delivered energy on the different types of windows are illustrated in below *Table 15.*

Table 15: The delivered energy comparison for various windows

	OP-06	OP-07	OP-08	OP-09	OP-10	OP-11
Lighting, facility	306,4	306,4	306,4	306,4	306,4	306,4
Electric cooling	697,2	863,3	1005,6	1499,9	641,4	638,8
Electric heating	7412,4	7372	7388,2	7567,9	7541,6	7516,7
Equipment,	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3
Total	11569,3	11695	11853,5	12527,5	11642,7	11615,2

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 43*).

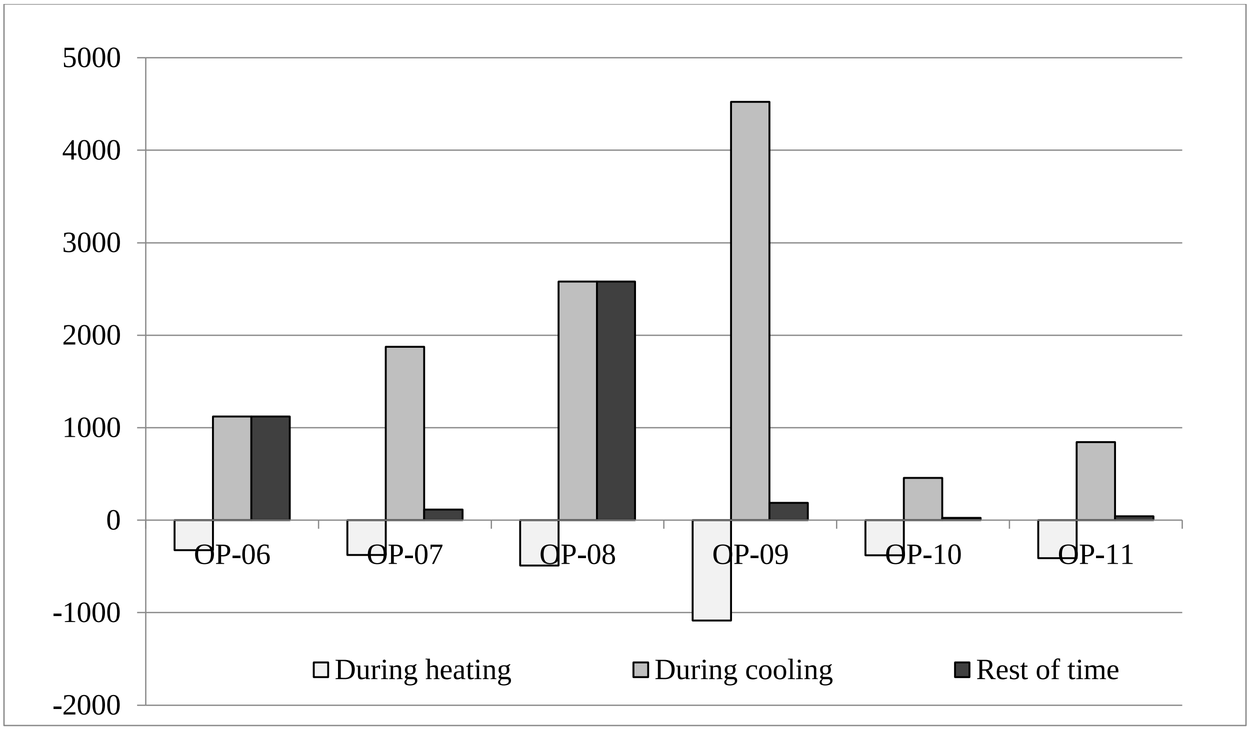

Figure 43: Energy balance, window and solar (kWh)

__Thermal comfort:__ Comparison of thermal comfort for the 6 type of windows is illustrated in below *Figure 44*. OP-07 shows the best result and the OP-9 shows the least.

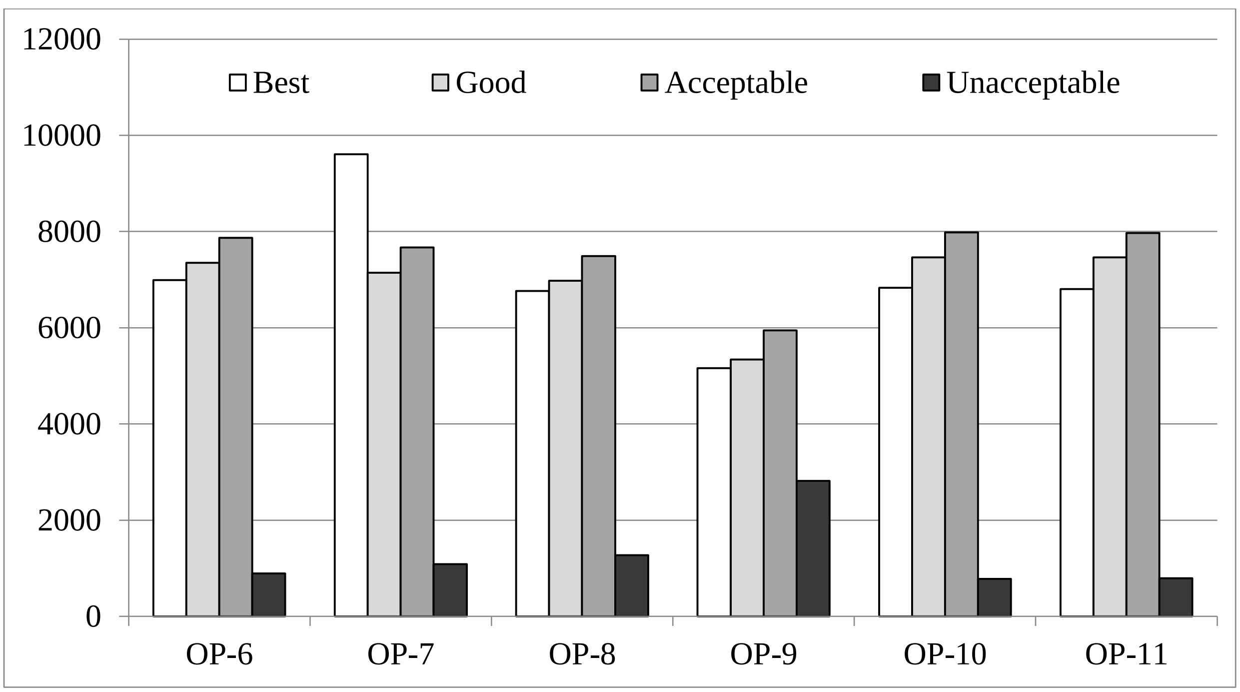

Figure 44: Thermal comfort comparison for the window of the yurt with numbers of occupancy hours.

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

To improve the door insulation, the 12mm 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^2K). From the thermal dynamic simulation result, the door heat loss is potential to be decreased to 153.8 kWh after the new insulation.

5.2.2. 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 towards; in exceptional or special circumstance different orientation is chosen [1, 2].

Simulation result for the orientation: The orientation compression of the yurt system energy is calculated using thermal dynamic simulation. And the results are shown in below 18 *Table 16*. In system energy setting, no significant difference was found except the little bit higher results shown in south and south-east orientation. And In *Table 17*, the results on delivered energy of the different orientations are compared, but which shows the same result as the system energy results.

Table 16: Orientation compression of the system energy

	OR-S	OR-SW	OR-W	OR-NW	OR-N	OR-NE	OR-E	OR-SE
Cooling	291,5	293,6	291,1	289,9	287,9	289,6	290,9	292,9
Heating	10101,2	10116,8	10163,4	10131,1	10124,1	10106,3	10131,4	10087,8
Total	10392,7	10410,4	10454,5	10421	10412	10395,9	10422,3	10380,7

Table 17: Orientation compression of the Delivered energy for the yurt

Meter	OR-S kWh	OR-SW kWh	OR-W kWh	OR-NW kWh	OR-N kWh	OR-NE kWh	OR-E kWh	OR-SE kWh
Lighting, facility	306,4	306,4	306,4	306,4	306,4	306,4	306,5	306,4
Electric cooling	291,5	293,6	291,1	289,9	287,9	289,6	290,9	292,9
Electric heating	10101,2	10116,8	10163,4	10131,1	10124,1	10106,4	10131,4	10087,9
Equipment, tenant	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3
Total	13852,4	13870,1	13914,2	13880,7	13871,7	13855,7	13882,1	13840,5

The results on thermal comfort comparative graphics of the different orientations are illustrated in *Figure 45*. The results for orientations show the same findings which indicate that orientation 5 do not effect yurt thermal comfort.

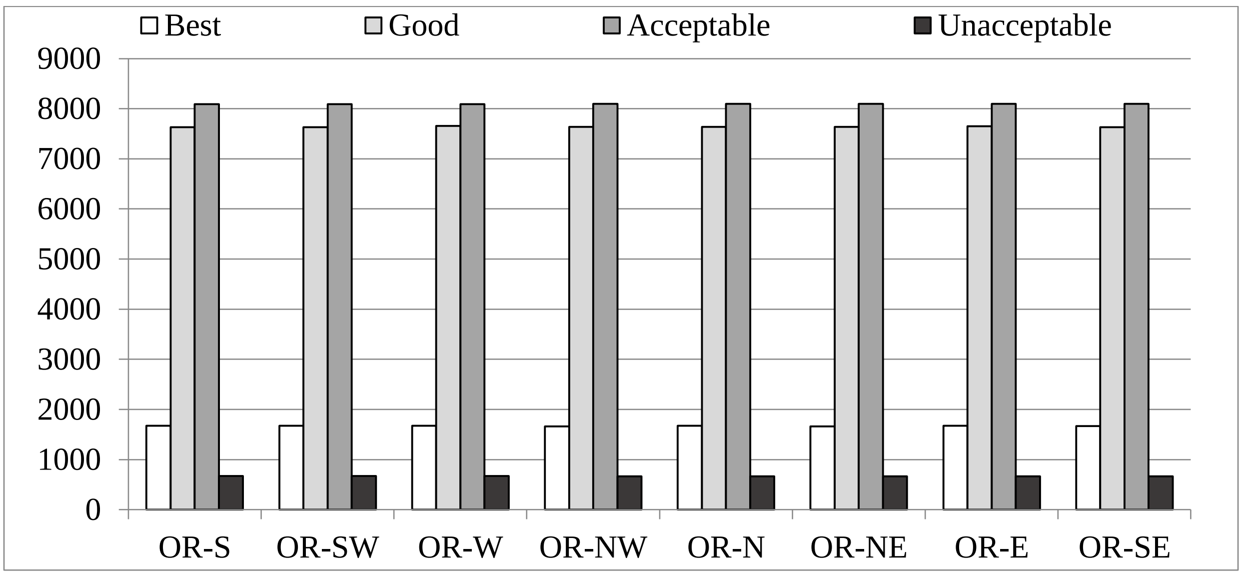

Figure 45: Comparative of the thermal comfort for the different orientations.

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.

Figure 46 illustrates diagrams of the Mongolian 21 provinces and capital city orientation, which is collected from the standard publication [216]. The illustrated diagrams are numbered from 10 to 0 and colored by light to dark with regards the best to the worst category. The best orientations are usually the south, south-east, and south-west and the worst orientations are north, north-west and northeast because it is related to wind and solar radiation directions.

Figure 46: Diagram of the Mongolian orientation follows the climate data (All 21 provinces and capital city), [60]

5.2.3. Structures, materials

<u>*Simulation results for comparison of different materials*, *SM-01to SM-08*</u>*:* The materials which are currently used and potential to be used are systemized in *Table 18*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 18: Materials, material density, material thermal conductivity [61] [62] [63] [64] [65] [66] [67] [68] [69]

materials	density kg/m3	thermal conductivity W/(mK)
Sheep wool felt	70	0,04
Rockwool	45-75	0,039
Glass wool	30	0,032
Mineral wool	145	0,0358
Sheep wool insulation	30	0,039
Silica aero gel blanket	120	0,0135
VIP	200	0,004
PCM	900	0.5
Membrane	302,2	0,0662
Tarpaulin	250	0,09
Cortex	646,57	0,04332

The various materials for wall and roof are tested for thickness, U-value of yurt and U-value of wall and roof and which are illustrated in *Table 19*. Material selection for yurt is crucial as significant heat is lost from 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 simulation while setting the same thickness for all materials (*Table 19*). The U-value of the yurt and wall, roof U-value is calculated by the thermal dynamic simulation tool - IDA-ICE 4.8 based on the material density, specific heat, and thermal conductivity.

Table 19: 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

Type of the yurt	Materials	material thick [mm]	U-value of the yurt, [W/(m2K)]	Wall and roof U-value [W/(m2K)]
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 47 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.

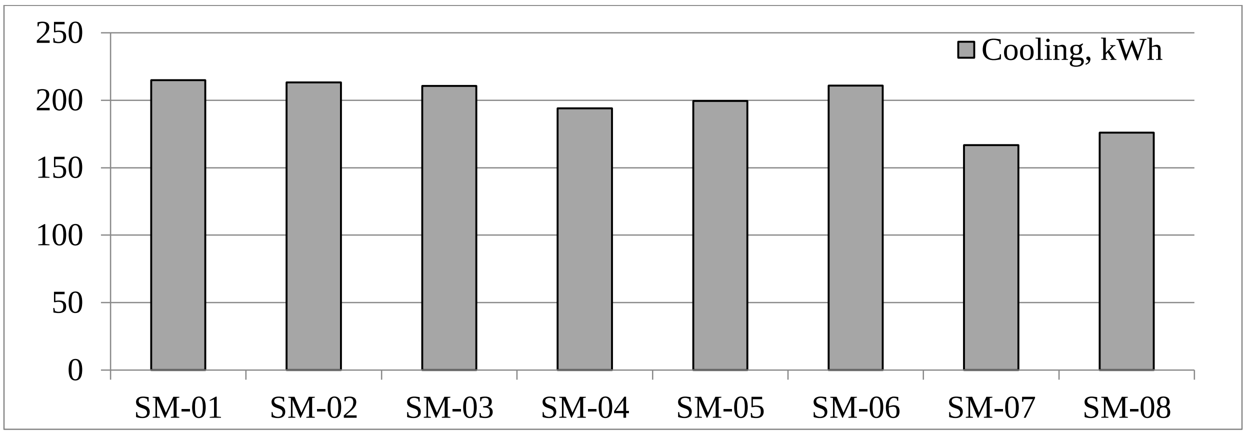

Figure 47: Electric cooling in system energy of different materials for the yurt (kWh).

Figure 48 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.

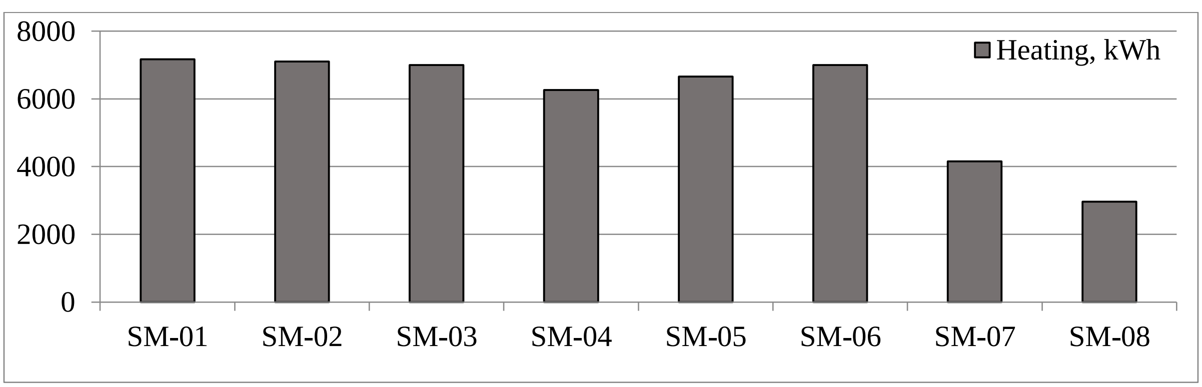

Figure 48: Electric heating in system energy of different materials for the yurt

Table 20 shows the thermal dynamic simulation result on delivered energy of different materials.

Table 20: Delivered energy of the yurt with the different material.

Meter	SM-01 kWh	SM-02 kWh	SM-03 kWh	SM-04 kWh	SM-05 kWh	SM-06 kWh	SM-07 kWh	SM-08 kWh
Lighting, facility	306,5	306,5	306,5	306,5	306,5	306,5	306,5	306,5
Electric cooling	107,4	106,6	105,3	96,98	99,72	105,4	83,34	88,02
Electric heating	7172,9	7105,4	7004,8	6266,2	6664	7003,8	4151,8	2968,8
Equipment,	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3
Total	10740,1	10671,8	10569,9	9822,98	10223,5	10569	7694,9	6516,6

Table 21 shows the energy balance of yurts with different materials. The most heat is lost from envelope and thermal bridge.

Table 21: Energy balance of different materials for the yurt

	Envelope & Thermal bridges, kWh	Window & Solar, kWh	Infiltration & Openings, kWh	Occupants, kWh	Equipment, kWh	Lighting, kWh
SM-01	-8142,7	-200,6	-874,1	2042,8	329,1	306,5
SM-02	-8078,3	-200,3	-874,3	2043	329,2	306,5
SM-03	-7978,3	-200,4	-874,1	2043	329,1	306,5
SM-04	-7250,2	-202	-875,2	2043,4	329,2	306,5
SM-05	-7645,1	-201,8	-875,6	2043,8	329,2	306,5
SM-06	-7645,1	-201,8	-875,6	2043,8	329,2	306,5
SM-07	-5142,3	-207,1	-881,2	2043,6	329,1	306,5
SM-08	-3932,8	-210,9	-886,2	2040,6	329,1	306,5

Table 22 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 developed yurt applied with different material shows 14 times less heat loss than the traditional yurt as illustrated in *Table 21*. 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.

Table 22: Heat loss from the details of a yurt in heat balance

	Walls and roof, kWh	Floor, kWh	Thermal bridges, kWh
SM-01	-4869.4	-1357.1	-2161.8
SM-02	-4803.9	-1358.2	-2162.1
SM-03	-4705.7	-1356.8	-2162.4
SM-04	-3967.0	-1364.4	-2165.5
SM-05	-4368.4	-1358.8	-2163.3
SM-06	-4368.4	-1356.6	-2162.4
SM-07	-1781.3	-1396.0	-2180.5
SM-08	-565.8	-1429.2	-2195.2

Thermal comfort of different materials is categorized into best, good, acceptable and unacceptable levels as illustrated in *Figure 49*. SM-08 shows no unacceptable category thermal comfort and SM-07 shows only 12 hours of the unacceptable thermal comfort.

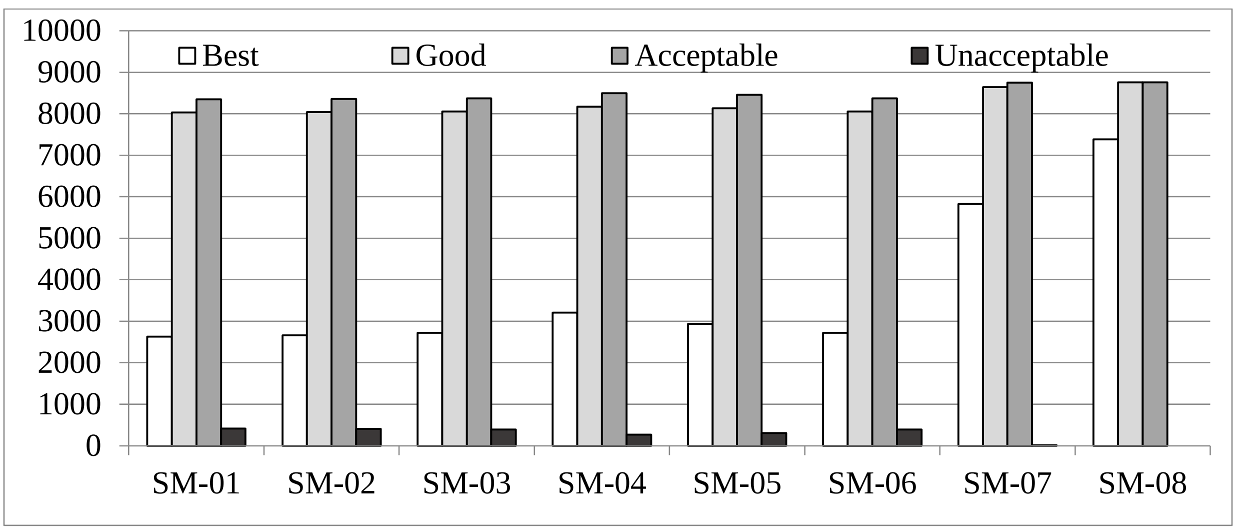

Figure 49: Thermal comfort of the different materials for the yurt with numbers of occupancy hours.

From the materials insulation comparison, VIP and Silica aerogel blanket show the best results. However, VIP material is not flexible and which makes it not suitable for yurt.

<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 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

lite. In this case study, the maximum thickness for the insulation material is set as 100mm insulation, 40mm PCM and coverage material (*Table 22*).

Table 23 shows systemization of materials, material thickness, U–value of the yurt and U-value of wall and roof for the different materials.

Table 23: 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/(m^{2}K)]	Wall and roof U-value [W/(m^{2}K)]
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 50 illustrates the electrical cooling in the system energy of different material for the yurt. For cooling, PCM shows effect on SM-12 and SM-13.

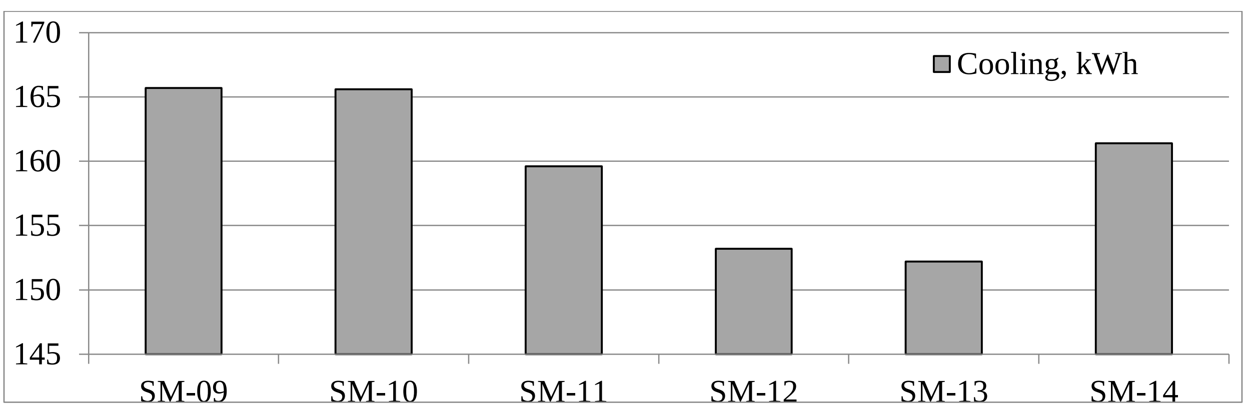

Figure 50: Electric cooling in system energy of different materials for the yurt (kWh), SM-09 to SM-14.

The insulation material thickness is directly related to the heating. In*Figure 51* illustrates the electrical heating 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 100mm which is Silica aerogel blanket.

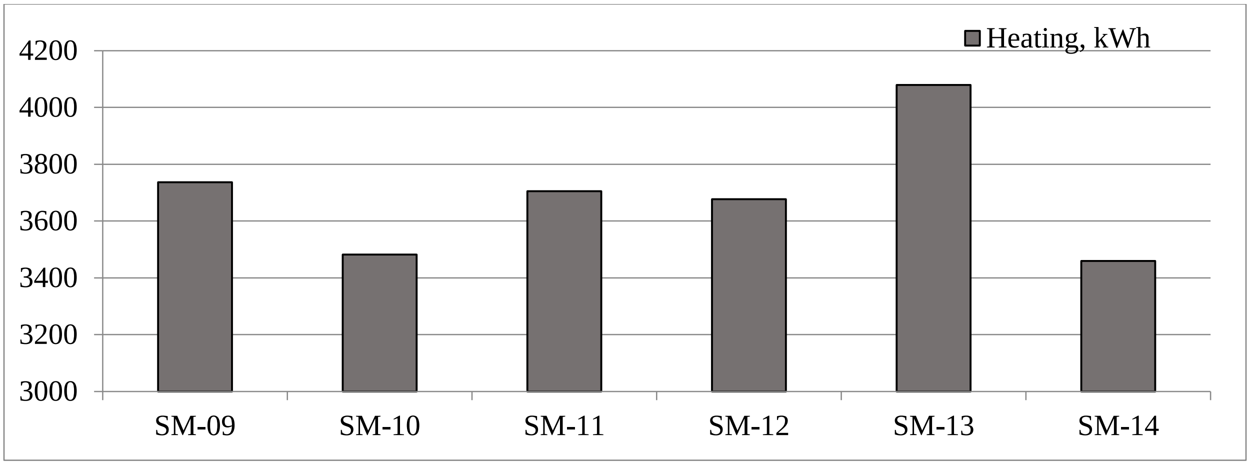

Figure 51: Electric heating in system energy of different materials for the yurt (kWh), SM-09 to SM-14.

Table 24 shows delivered energy of different materials (SM-09 to SM-14) and the best outcomes are highlighted in grey.

Table 24: Delivered energy of the yurt with the different material, SM-09 to SM-14

	SM-09	SM-10	SM-11	SM-12	SM-13	SM-14
Lighting, facility	306,5	306,5	306,5	306,5	306,5	306,5
Electric cooling	82,87	82,82	79,82	76,59	76,1	80,72
Electric heating	3737	3482,3	3705,5	3676,3	4079	3459,6
Equipment, tenant	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3
Total	7279,7	7024,9	7245,1	7212,7	7614,9	7000,1

Table 25 shows the energy balance of the different materials for the yurt. Except for the envelope and thermal bridge results, other results show almost the same amounts.

Table 25: Energy balance of different materials for the yurt SM-09 to SM-14.

	Envelope & Thermal bridges, kWh	Window & Solar, kWh	Infiltration & Openings, kWh	Occu-pants, kWh	Equip-ment, kWh	Lighting, kWh
SM-09	-4725,5	-207,8	-883	2043,2	329,1	306,5
SM-10	-4469,8	-208,4	-884,2	2042,7	329,2	306,5
SM-11	-4704,5	-207,4	-883,6	2043,4	329,2	306,5
SM-12	-4684,8	-206,6	-883,7	2043,4	329,2	306,5
SM-13	-5089,5	-206,5	-882,2	2044,3	329,2	306,5
SM-14	-4455,5	-207,8	-884,5	2042,7	329,2	306,5

In*Table 26* illustrated the total heat loss from the envelope area and thermal bridge of the heat balance. Walls and roof heat loss are different because the material thickness is different.

Table 26: Heat loss from the details of a yurt in heat balance, SM-09 to SM-14.

	Walls and roof, kWh	Floor, kWh	Thermal bridges, kWh
SM-09	-1386,9	-1405.8	-2185.0
SM-10	-1120,9	-1412.9	-2187.7
SM-11	-1361,5	-1407.4	-2185.0
SM-12	-1337,7	-1409.5	-2185.2
SM-13	-1757,6	-1398.8	-2180.8
SM-14	-1102,9	-1414.4	-2187.9

In *Figure 52*, the thermal comfort of the different materials are compared in terms of occupancy hours during the year are illustrated. The best category is the highest for SM-14 and unacceptable category for SM-14 shows 0 hours and the other yurts are between the 1 to 7 hours in *Figure 52.*

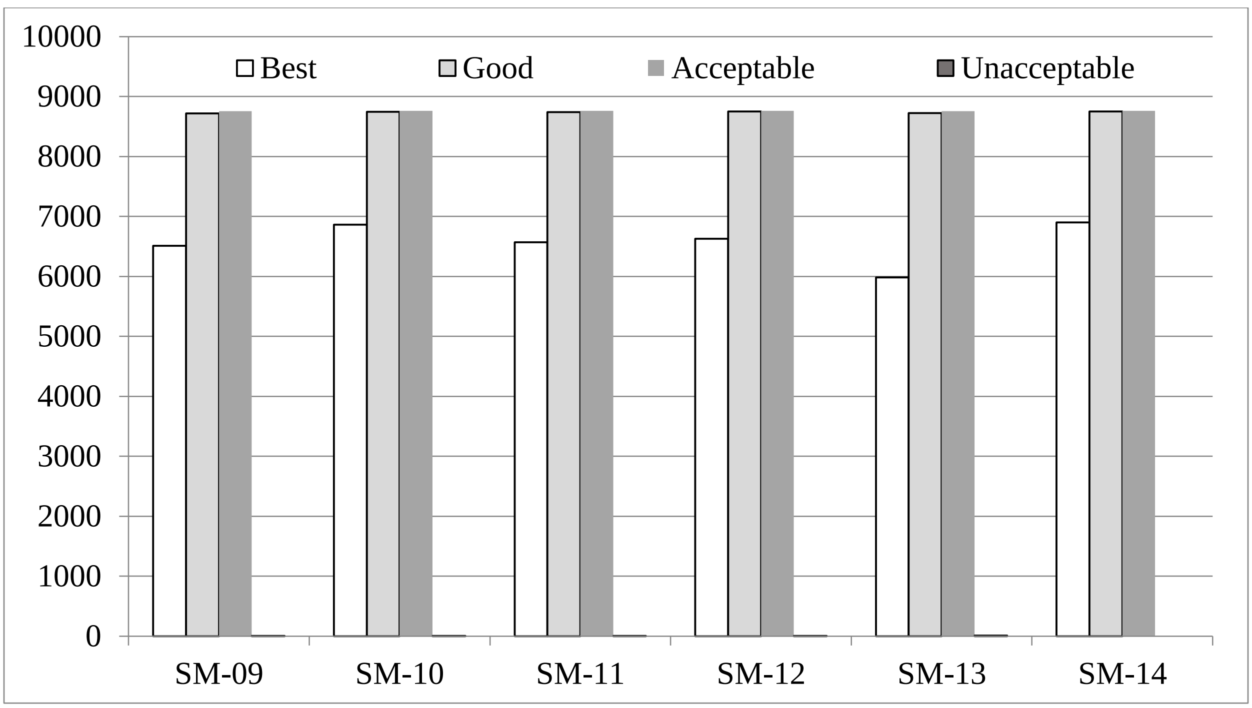

Figure 52: Thermal comfort of the different materials for the yurt with numbers of occupancy hours, SM-09 to SM-14.

5.2.4. Combination of the Opening and Structural material

From the previous results, OP-03 shows the best opening results for yurt which has a big top opening with 3 pane glasses with no window at the wall.

The best result of Structural material character is SM-14 with the tarpaulin, Silica aerogel blanket, and PCM, and the total U- value for the wall and roof is 0,1302 W/(m^2K). 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 27* illustrated the delivered energy for the combination of the opening and structural material.

Table 27: 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

Table 28 illustrates energy balance results which show the heat loss from the envelope and thermal bridge is decreased approximately by three times compared with the existing yurt.

Table 28: Energy balance for the combination of the opening and structural material.

	Envelope & Thermal bridges, kWh	Window & Solar, kWh	Infiltration & Openings, kWh	Occu-pants, kWh	Equip-ment, kWh	Lighting, kWh
Total	-3347,3	435,3	-927,3	2000,9	3153,3	306,4
During heating	-945,3	-75,7	-567,8	388,1	637,5	67,6
During cooling	-1878,6	511,9	-267,3	1379,4	2147,2	199,5
Rest of time	-523,4	-0,9	-92,2	233,4	368,6	39,3

The heat loss from the envelope area (roof and wall) has been decreased by 7 times compared with existing yurt. The door which is insulated with the Silica aerogel blanket is also decreased the heat loss as shown in *Table 29*.

Table 29: Heat loss and heat gain from the envelope and thermal bridge for the combination of the opening and structural material.

Month	Roof &wall	Floor	Windows	Doors	Thermal bridges
Total	-1155,1	-1504.3	-240.8	-69.3	-734.9
During heating	-408,2	-292.5	-79.9	-21.9	-254.5
During cooling	-527,8	-1025.0	-121.4	-34.5	-351.4
Rest of time	-219,1	-186.8	-39.5	-12.9	-129.0

In*Figure 53* 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 yurt and combination yurt due to the simulation model has not set ventilation for the calculation.

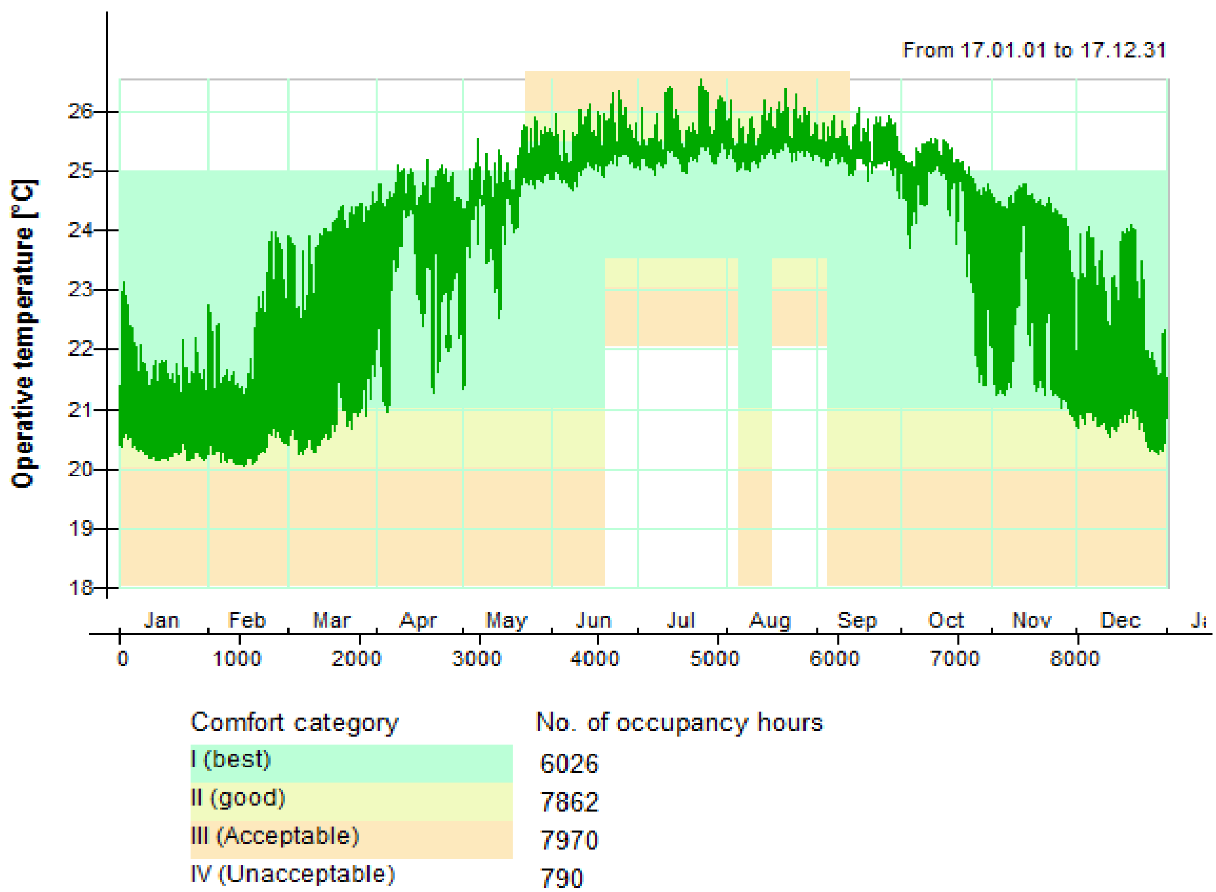

Figure 53: Thermal comfort for the combination of the opening and structural material.

5.2.5. Building services systems

The development of the building service system used 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 30* along with the number of heater and heater power.

Table 30: 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	Floor heating	16m2	2500
SY-05	Heating cooling panel	1	2500
SY-06	Simple fan coil	1	2500
SY-07	Simple fan coil	2	2500*2
SY-08	Floor heating	16m2	5000

From the *Table31*, the result of the minimum temperature and minimum operative temperature shows very low results for SY-04 and SY-08 which potentially caused by a floor heating system for the yurt has applied. The Floor heating surface temperature has automatically set on the simulation tool. The floor surface temperature is required to meet an acceptable level as the floor directly contact with human body. Except the above two heating, others work normally for yurt heating. *Table 31* illustrates maximum heat supplies, room unit heat, and maximum CO_2 ppm of the different heating system for the yurt. The best results on the CO_2 level are SY-03 and SY-05, which have standard AHU. The best results on maximum PPD percent are SY-01 and SY-02.

Table 31: 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, %	Max CO2, ppm (vol)
SY-01	21,03	25,05	20,89	26,53	22,57	82,5	14,1	19804
SY02	20,34	25,06	20,81	26,67	23,2	81,39	14,6	19871
SY-03	20,38	26,69	19,9	27,14	16,85	71,43	26,38	1101
SY-04	12,76	27,06	14,07	28,97	85,71	85,71	89,99	20844
SY-05	20,94	26,69	20,13	27,13	9,936	67,39	22,51	1102
SY-06	20,82	25,06	19,62	26,67	9,479	68,29	23,63	19870
SY-07	20,96	25,02	19,67	26,67	8,179	68,18	24,41	19301
SY-08	14,51	27,08	15,91	28,97	169,1	178,6	72,59	20843

Table 32 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, which is received simulation result.

Table 32: System heating energy for the difference of the heating (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	474,5	1513,3
AHU heating	0	0	1581,1	0	1584,7	0	0	0
Total heating	685,9	672,9	2316,1	1204,7	2263,7	0	474,5	1513,3

Table 33 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-06 with a simple fan coil with 2500 W power.

Table 33: 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	2367,7	2352	2544,2
HVAC aux	0	0	695,2	0	694,3	0	59,82	0
Electric heating	685,9	672,9	2316,2	1204,7	2263,7	579,7	582,7	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	6407,1	6454,3	7517,2

Table 34 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.

Table 34: Thermal comfort for the yurts with the different heating system.

	Best	Good	acceptable	Unacceptable
SY-01	7293	8055	8105	655
SY-02	6825	7796	7885	875
SY-03	4689	7637	7687	1073
SY-04	1504	1681	2207	6553
SY-05	5025	7566	7683	1077
SY-06	4715	7145	7897	863
SY-07	4689	7127	7888	872
SY-08	1186	1309	1713	7047

Cooling and Ventilation

Natural ventilation for the yurt: The yurt has natural ventilation, with the top opening and under the wall as called as "Dome chilling effect" [40]. 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 hottest 2 months in between 15th of June to 15th of August. An opening is located in the north side lower edge of the wall (*Figure 54*). The simulation conducted without any energy for the heating and cooling. The main point is to analyze how the natural ventilation of traditional yurt works.

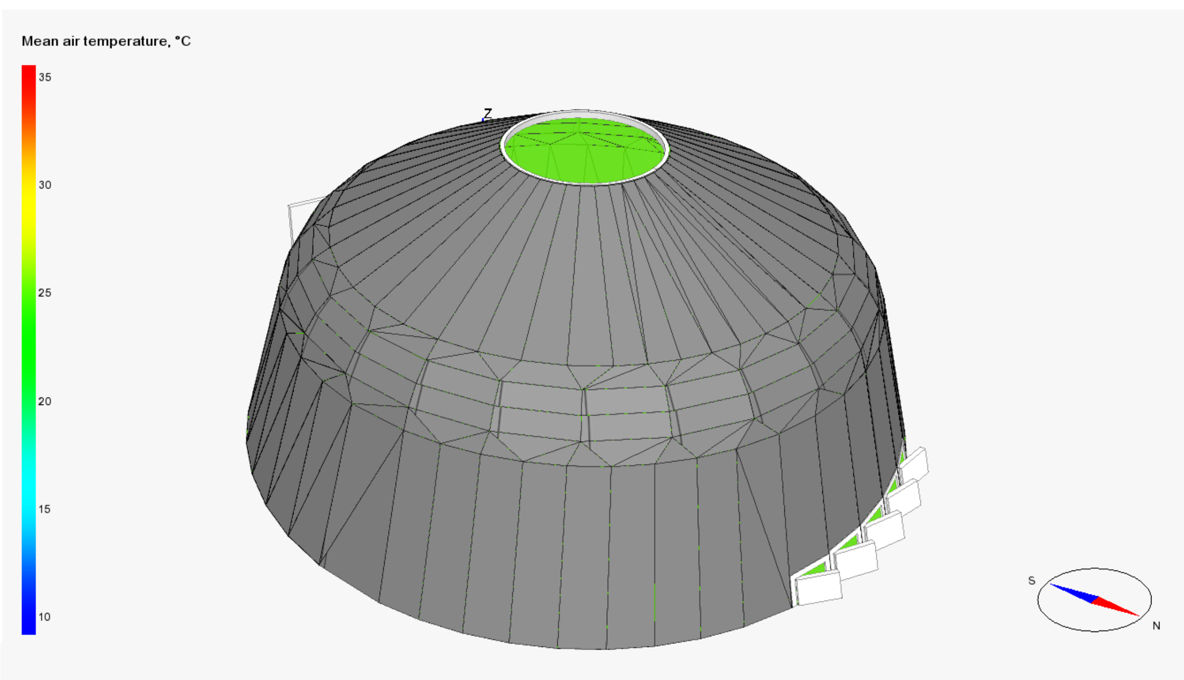

Figure 54: The yurt with the khayaa, for the natural ventilation.

Figure 55 illustrates the mean temperature of the yurt with natural ventilation. The schedule of the khayaa is set between 12:00 and 15:00 and height of the opening 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 55* and *Figure 56.* The mean temperature starts to increase from 16:00 due to the khayaa is closed.

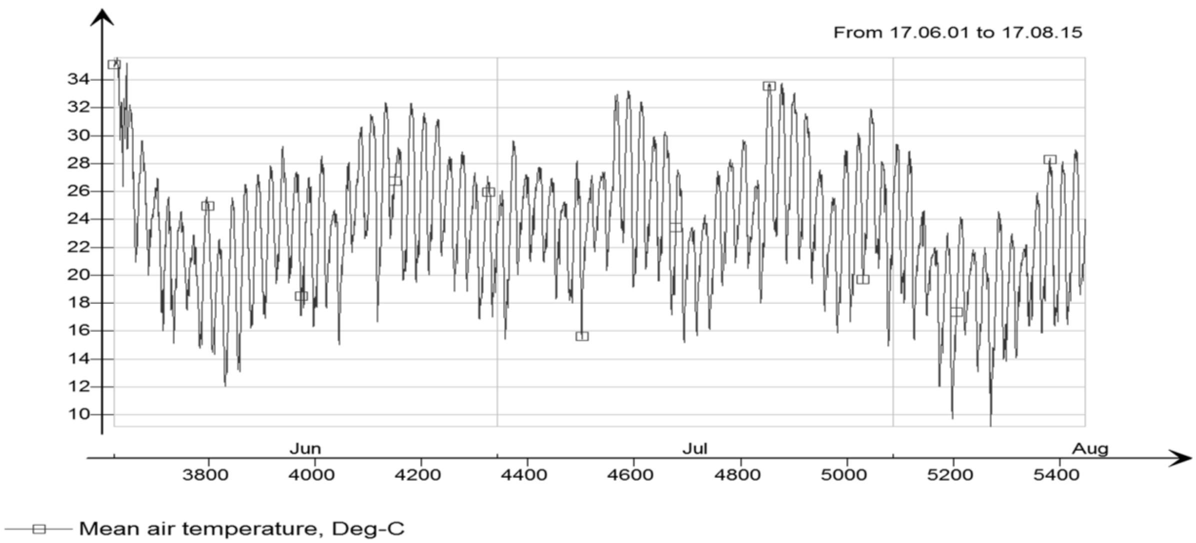

Figure 55: Mean temperature of the yurt with natural ventilation (2 months)

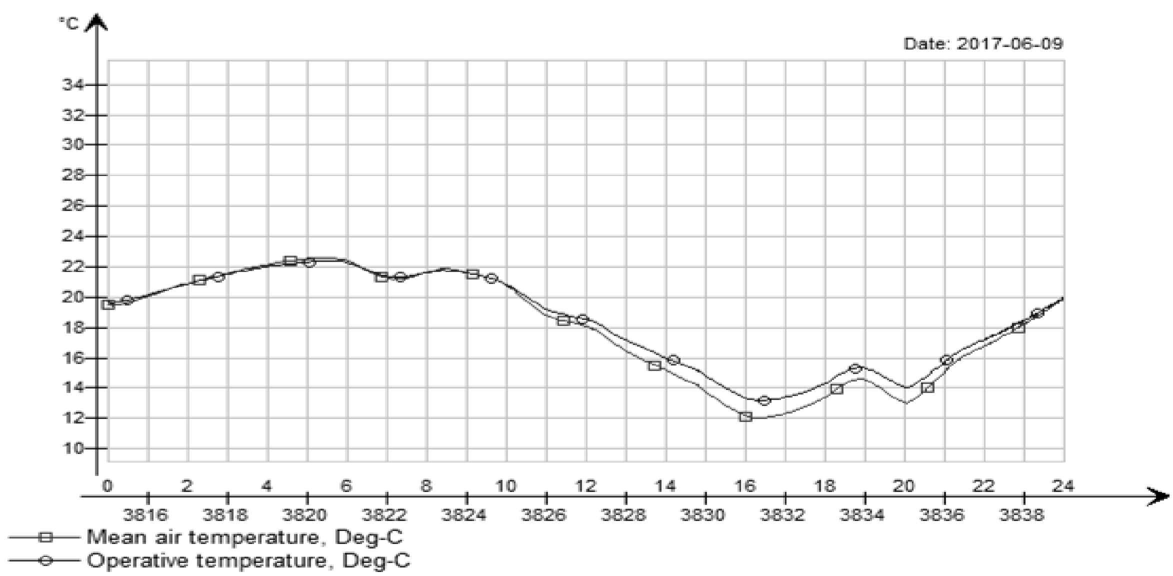

Figure 56: Mean temperature of the yurt with natural ventilation for a day.

Figure 57 illustrates the thermal comfort between June to August. The unacceptable level of thermal comfort shows warm in the night and cool in the day due to the ventilation cools down in the daytime.

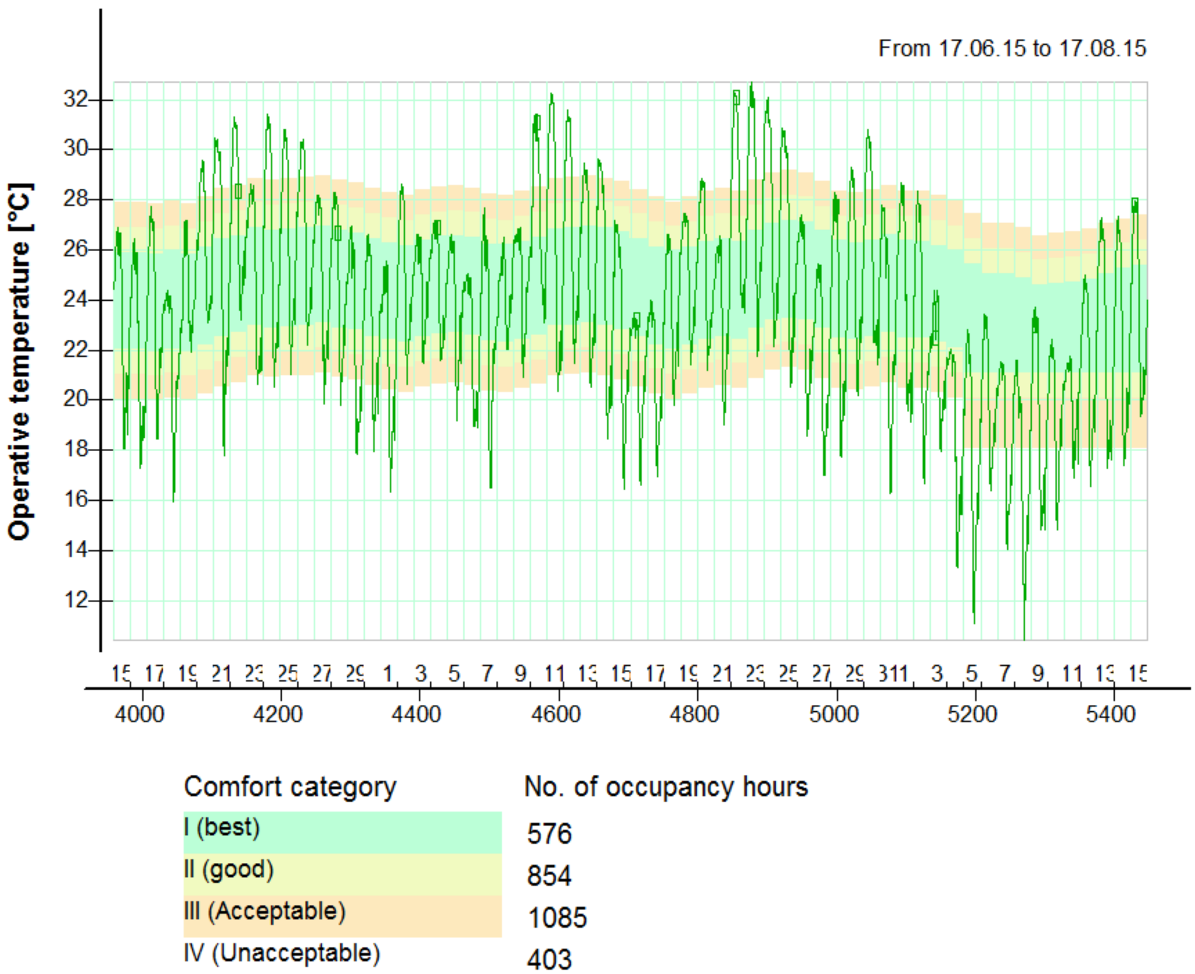

Figure 57: Thermal comfort of the yurt between the June to August.

Figure 58 illustrates the CO_2 (ppm) of the yurt with the natural ventilation. The CO_2follows the openings: door, top opening, and khayaa. From the CO_2 diagram, the best result appears during opening of khayaa.

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 air ventilation.

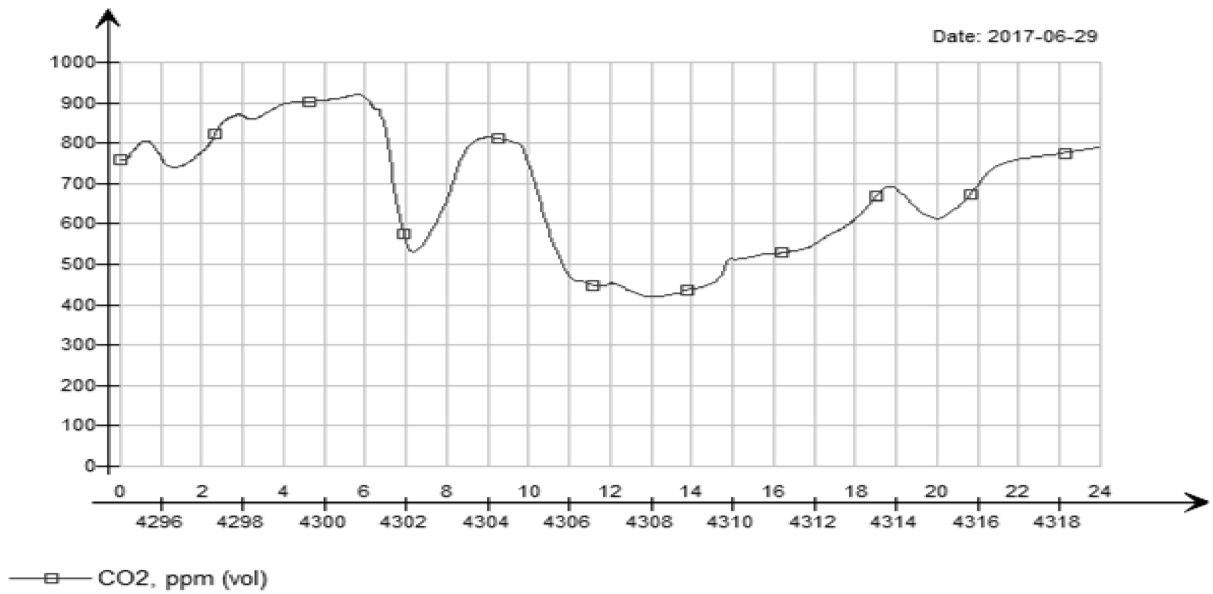

Figure 58: CO_2, ppm of the yurt during natural ventilation for a day.

<u>*Mechanical ventilation*</u>*:* For the ventilation simulation, the combination of natural and mechanical ventilation is tested, where natural ventilation is worked according to the defined schedule. *Table 35* illustrates different types of AHU for the yurt in the simulation. For the simulation, cooling element has not set because the natural ventilation is enough for the cooling in summer.

Table 35: Different types of the 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 36 illustrates the general information about yurts with the different AHU 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 maximum age of air and CO_2 level.

Table 36: 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 37 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 37: 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 38*, SY-11 has the best result on total heating and cooling energy in the system energy in the setting of different AHU.

Table 38: 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	0,05887	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 39 illustrates 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 39: The delivered energy of the yurt with the different AHU.

	SY-09	SY-10	SY-11	SY-12	SY-13	SY-14	SY-15
Lighting, facility	306,5	306,5	306,5	306,5	306,5	306,5	306,5
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
Equipment, tenant	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3	3153,3
Total	8144,4	7003	5887,5	7818,5	7563,3	9787,2	8144,4

In *Figure 59,* the thermal comfort of the yurt with the different AHU is illustrated. The SY-13 has best result of the thermal comfort and other yurts did not show high difference as shown in the Table.

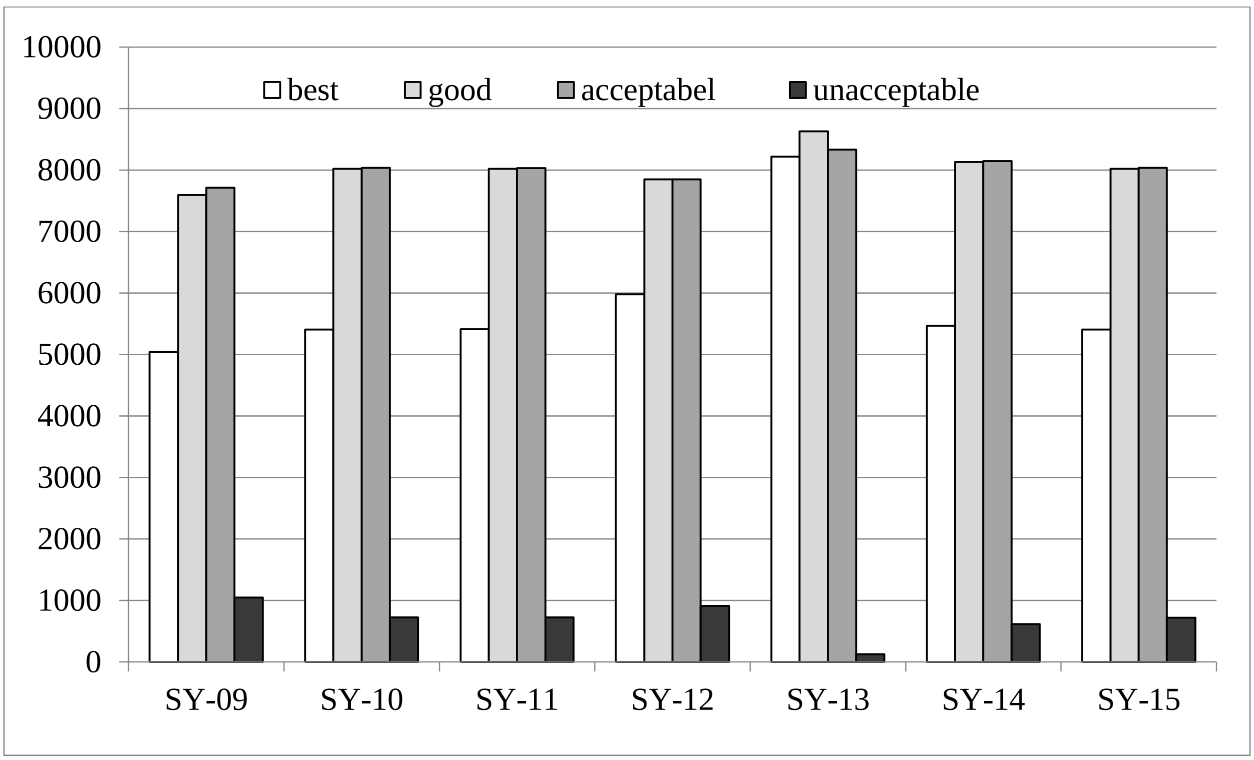

Figure 59: Thermal comfort of the yurt with the different AHU (8760h)

In *Figure 60,* 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 to 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.

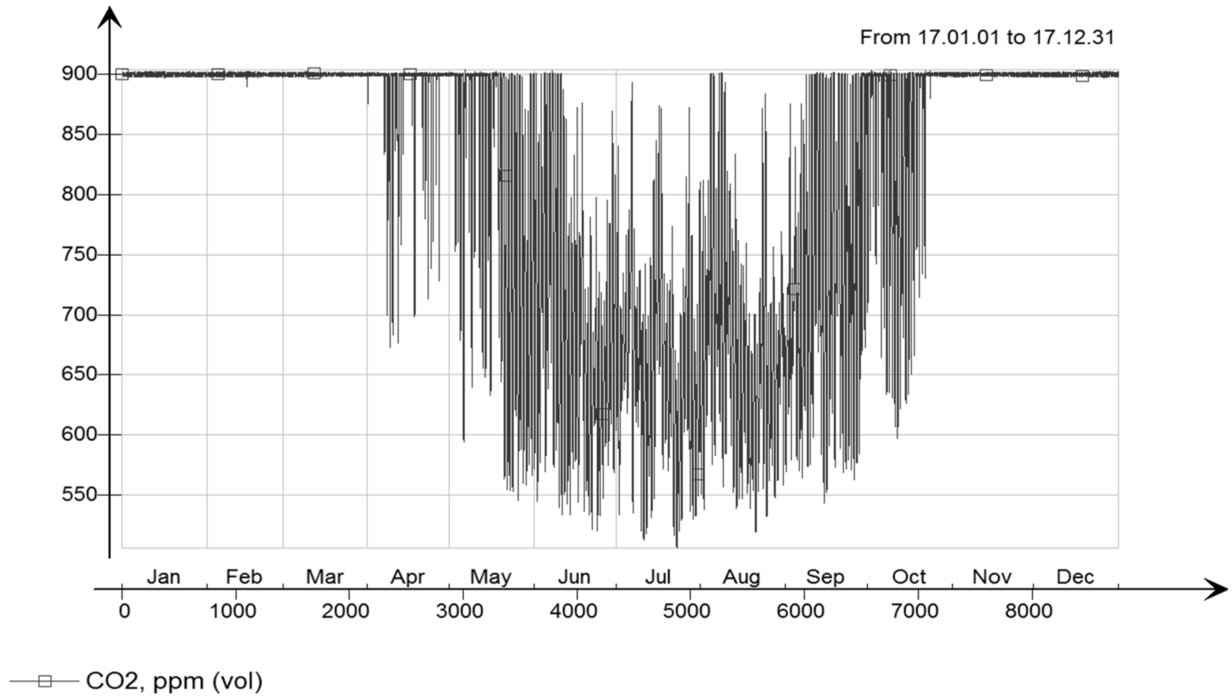

Figure 60: CO2, ppm for the SY-11.

5.3. Conclusions: the potential of the vernacular yurt

<u>*Opening*</u>

The development simulation has conducted for 11 versions of the opening in two parts. In the first part, 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.

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

The second part has used window on the envelope area following the glazing percentage for the cool climate condition. 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 increased energy efficiency. In terms of energy efficiency, it has found that windows are not suitable for yurt which is shown from OP-03 with best top opening results.

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. But the south-east, south, and south-west orientations show a better result.

Structural material

The aim of the study is to find the suitable insulation material for the yurt in Mongolian extreme climate.

Firstly, the lite weight and flexible insulation materials features are compared. For this comparison, all materials thickness has set as same and thermal conductivity, density 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 lite weight material.

At second, Silica aerogel blanket was simulated at 60mm, 80mm, and 100mm thickness with PCM and compared to find the suitable form of thickness for 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 roof, also in between the wooden wall and insulation material. For the cover material, any material including the tarpaulin, membrane, and Gore-Tex material is suitable with the condition that material should have water and wind protection.

System

Heating: The electric radiator and heating fan coil provide best result for the heating of yurt which is shown in SY-1 and SY-6. SY-01 shows best result on thermal comfort result.

Natural ventilation: Openings works very well in natural ventilation for the summer season. The top opening and khayaa are good combinations to ventilate the air. In simulation result which held 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 khayaa is set as opened and mean temperature has shown to be decreasing and during the closed time mean temperature was increased. The CO_2 level also directly related to openings. The natural ventilation provides the cooling of the yurt.

Mechanical ventilation: The mechanical ventilation is used in yurt during winter season because the natural ventilation cannot work in extremely cold winter with -40°C. The yurt has much heat losses from the openings. The SY-11 with the Enthalpy wheel AHU shows 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 in the system energy and delivered energy result.

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

6.1. Energy consumption of the traditional yurt

Below *Figure 61* illustrates thermal model of the mean temperature graphic of the 13th-century Mongolian yurt. The model boundary condition set to the real condition 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^2K).

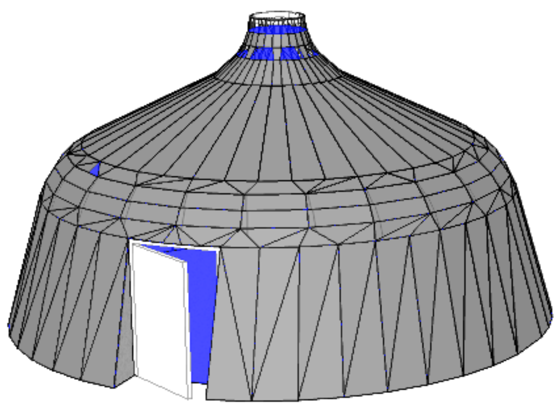

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Figure 61: 13th-century Mongolian existing yurt

The heating and cooling system energy and delivered the energy of the 13th-century Mongolian yurt is described in *Table40*. The total delivered energy includes lighting, facility and equipment energy.

Table 40: System energy and delivered energy for the 13th-century Mongolian yurt (Heating and cooling)

Systems energy

	kWh
Zone heating	10420,5
Zone cooling	260,3
Total	10680,8

Delivered Energy

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 41* 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 bridge as illustrated in below Table. The window & solar shows heat gain from the sun during the cooling and rest of time setting. Because the traditional yurt has no window at the wall instead of top opening and door provide the function.

Table 41: 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 42 shows envelop heat transmission of the 13th-century Mongolian yurt. From the result, the heat is mostly lost through the walls and roof.

Table 42: 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 62* illustrated the thermal comfort categories with occupancy hours of the existing yurt with the hourly resolute to the whole year.

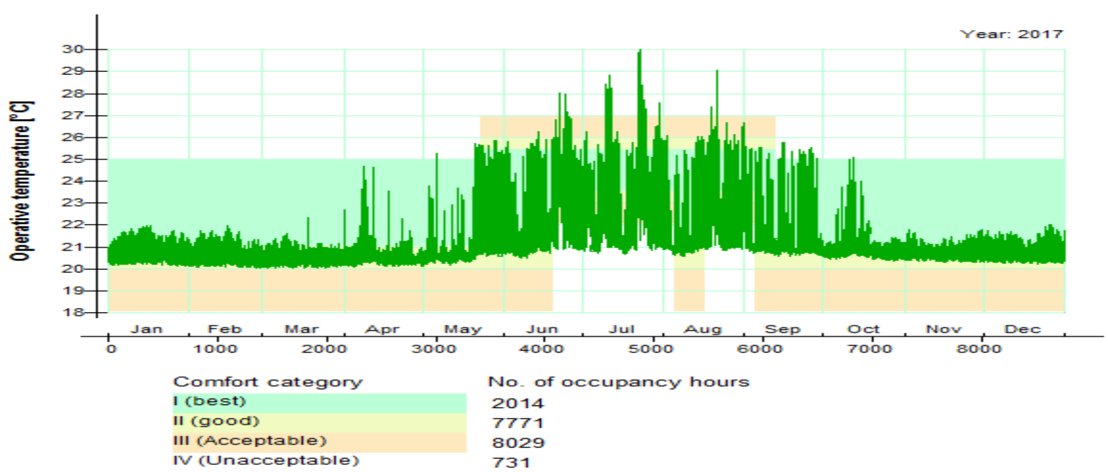


Figure 62: Thermal comfort of the exciting yurt.

Figure 63 illustrated the indoor air quality, indicated the CO_2 ppm level of the existing 13th-century Mongolian yurt.

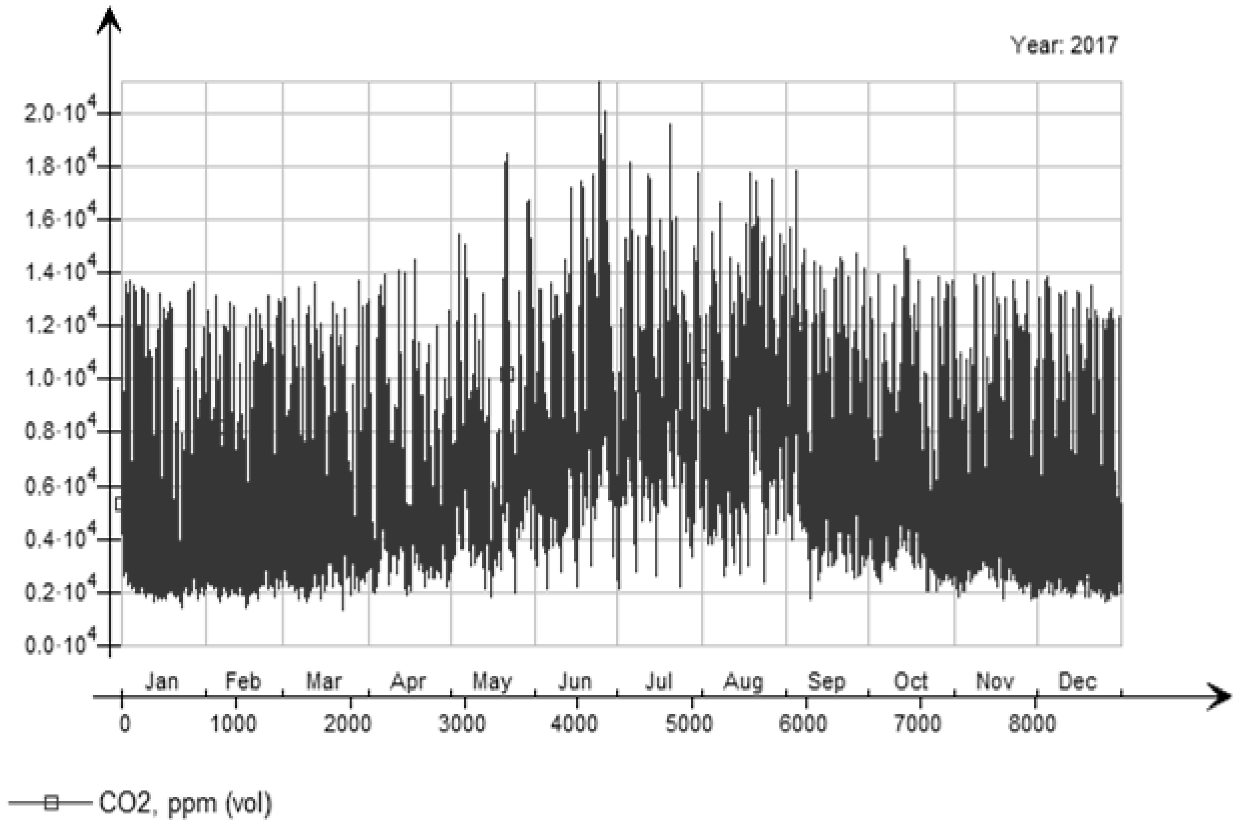


Figure 63: CO_2, ppm of the exciting yurt.

6.2. Combination and optimization of cases

The combined yurt is set in taking account of the best versions of characteristics (OP, OR, SM, SY). The combined yurt has a big top opening with three pane glazing, Silica aerogel blanket insulation material with PCM heat storage, simple fan coil heating system, and enthalpy wheel AHU with the natural condition.

Table 43 illustrates the system energy and delivered energy of the combined yurt model.

Table 43: System energy and delivered energy of the combined yurt with the optimized characters.

Systems energy

	kWh
Zone heating	2092,9
Zone cooling	83,31
AHU heating	904,6
AHU cooling	368,1
Cooling	451,4
Heating	2997,5
Total	3448,9

Delivered Energy

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	202,7	7,239	0,1291
Electric heating	2997,6	107,1	3,97
Equipment, tenant	3153,3	112,6	0,36
Total	7111,4	254	6,329

The energy balance of the combined yurt is shown in *Table 44*. Highest heat loss is found to be lost through envelope and thermal bridge.

Table 44: Energy balance of the combined yurt.

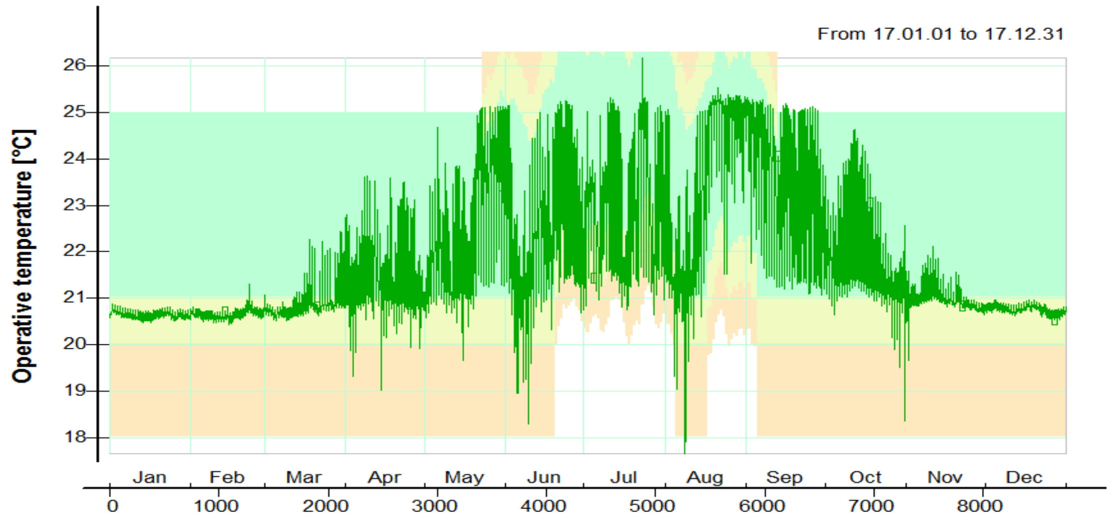
	Envelope & Thermal bridges,	Internal Walls and Masses,	Window & Solar, kWh	Mech. supply air, kWh	Infiltration & Openings, kWh
Total	-3110,2	-41,6	242,8	-2333,5	-2003,5
During heating	-2275,6	-32,1	-208,9	-1286,1	-1789,2
During cooling	-363,6	-2,7	259,2	-509,7	-28,2
Rest of time	-471	-6,8	192,5	-537,7	-186,1

Table 45 shows the envelope heat transmission of the combined yurt. From the result, the heat is mostly lost through the walls and roof.

Table 45: Envelop heat transmission of the combined yurt.

Month	Roof and wall	Floor	Windows	Doors	Thermal bridges
Total	-1057,1	-1419.6	-474.8	-63.3	-674.9
During heating	-909,1	-819.4	-421.7	-53.0	-580.3
During cooling	-46,5	-294.2	-10.3	-3.2	-25.4
Rest of time	-101,4	-306.0	-42.8	-7.1	-69.2

Figure 64 illustrates the thermal comfort of the combined yurt model.



Comfort category	No. of occupancy hours
I (best)	4474
II (good)	8484
III (Acceptable)	8703
IV (Unacceptable)	57

Figure 64: Thermal comfort of the combined model with comfort category and number of occupancy hours.

Figure 65 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.

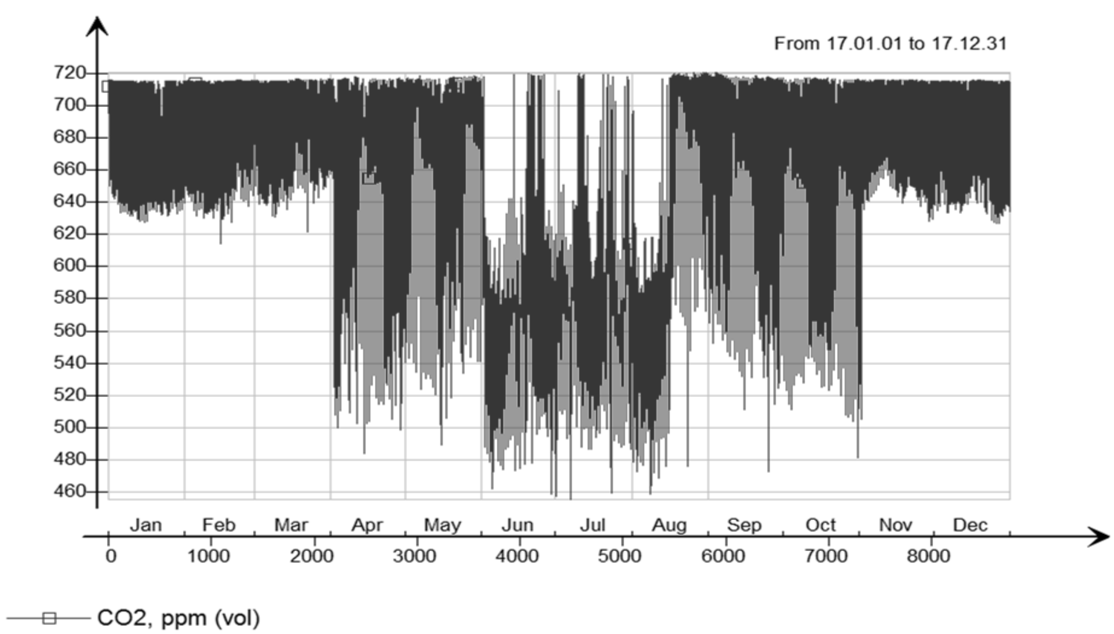


Figure 65: CO_2, ppm of the combined model.

6.3. Developed and optimized transportable building based on the yurt

The developed model is redesigned to meet energy efficient, highly indoor comfort and modern building requirement on the basis of traditional yurt. The developed model is optimized by the simulation tool. The yurt size can be changeable without changing the form. For the whole study, one family yurt size has been applied and development model has taken the size as a basis.

In *Table 46* illustrated types and dimensions of the developed yurt. The development of the yurt used the most energy efficient shape of the traditional yurt which has the lowest area ratio, investigated from the comparative analysis. Also in below table, various sizes of developable yurts are shown.

Table 46: Developed yurts and dimensions.

Types of yurt	Diameter	Area	Crown size	Height
Small yurt	5	19,6	1,25	2,25
Family yurt-1	6	28	1,5	2,7
Family yurt-2	8	50,2	2	3,6
Big yurt-1	10	78,5	2,5	4,5
Big yurt-2	12	113,4	3	5,4

The model has developed yurt with separate rooms which include cubicle (airlock), bathroom, bedroom, and living room with a kitchen. The developed yurt's form and structural material are same as the combined yurt and added windows to provide ventilation, daylighting and visual comfort due to the rooms are separated by walls. The windows should be three pane glasses and U-value is 0.7 W/ (m^2K) as it has recommended in Chapter 5 for the top-opening. The internal walls should be lightweight, portable and separable from the external walls. The wall structure has set with wooden panel, Silica aerogel insulation and PCM in the simulation.

Figure 66 illustrated the developed and optimized yurt drawing with plan, façade, and section which is developed based on the basis of previous studies discussed in Chapter 4 and 5.

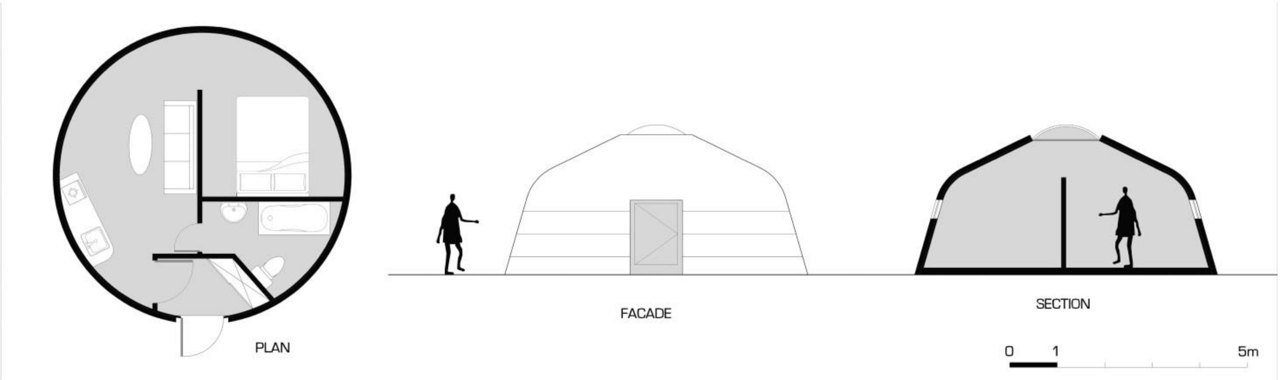


Figure 66: Drawing of the developed and optimized yurt with plan, façade, and section (Family yurt-1).

Table 47 shows developed yurt's heating, cooling lighting, equipment, and AHU energy as part of system energy and delivered energy from the simulation result.

Table 47: Developed yurt's System energy and delivered energy.

Systems energy

	kWh
Zone heating	1707,9
Zone cooling	114,9
AHU heating	797,3
AHU cooling	330,8
Cooling	445,7
Heating	2505,2
Total	2950,9

Delivered Energy

Meter	Total, kWh	Per m2, kWh/m2	Peak demand, kW
Lighting, facility	306,4	10,94	0,14
Electric cooling	445,8	17,68	1,489
HVAC aux	182,1	7,224	0,06751
Electric heating	2702,9	107,2	2,527
Equipment, tenant	3153,3	112,6	0,36
Total	6790,5	255,644	4,58351

In Table 48 shows the energy balance of the developed yurt.

Table 48: Energy balance for developed yurt,

	Envelope & Thermal bridges, kWh	Internal Walls and Masses, kWh	Window & Solar, kWh	Mech. supply air, kWh	Infiltration & Openings, kWh
Total	-2215	-197,7	185,6	-2035,7	-1117,5
During heating	-1537,6	-145,1	-379	-872,4	-1004
During cooling	-179,7	-25,4	303,7	-431,7	-90,1
Rest of time	-497,7	-27,2	260,9	-731,6	-23,4

Table 49 illustrates the envelope heat transmission of the developed yurt. Highest heat loss happens through the wall and roof.

Table 49: Envelop heat transmission of the developed yurt,

Month	Wall and Roof	Floor	Windows	Doors	Thermal bridges
Total	-951.7	-798.8	-539.9	-387.3	-659.9
During heating	-756.8	-450.1	-448.1	-379.7	-528.5
During cooling	-30.7	-127.7	-14.8	04.I	-20.8
Rest of time	-170.2	-221.0	-77.0	-9.0	-110.6

In*Figure 67* illustrates the thermal comfort of the developed yurt's bedroom with thermal comfort categories and number of occupancy hour.

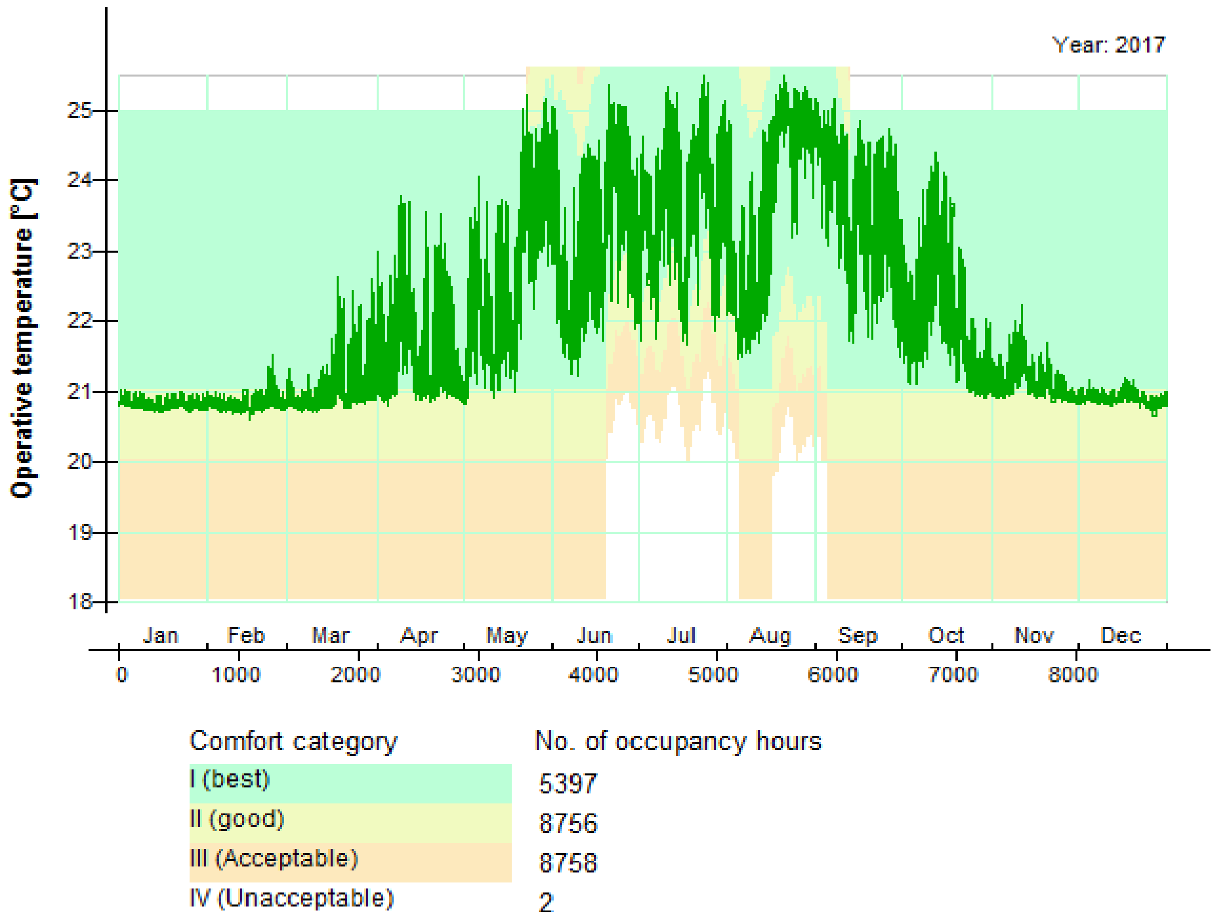


Figure 67: Thermal comfort of the developed yurt with the comfort categories and number of occupancy hours.

In Figure 68 illustrates the CO_2 level of the developed yurt from the simulation result. The CO_2 level is between 520ppm to 740 ppm which indicates the indoor air quality is high.

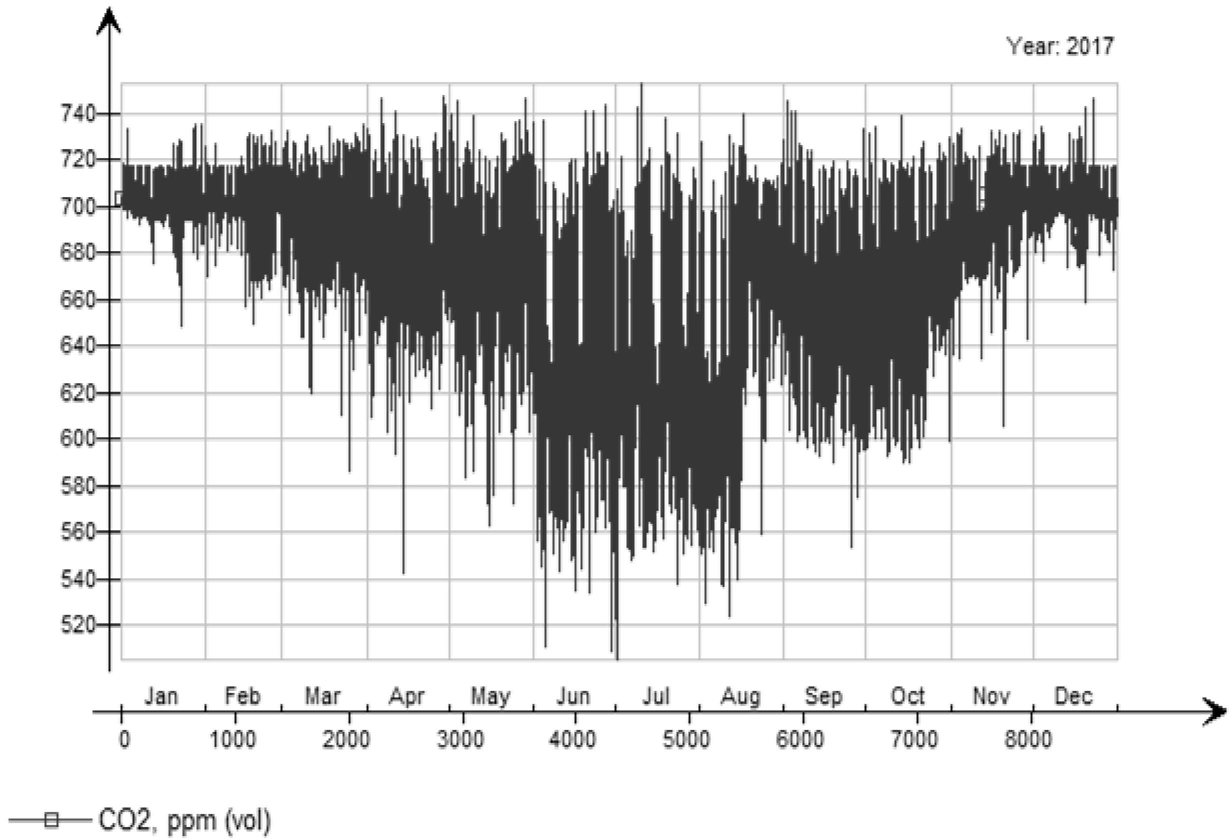


Figure 68: CO_2, ppm of the developed yurt.

In*Figure 69* illustrates the developed yurt with bigger size (Family yurt-2). The yurt is divided with cubicle, living room with kitchen, bathroom, and two bedrooms by internal walls. The yurt has potential to get enlarged or downsized while keeping the optimal shape and it is easy to change the architecture planning by the lightweight and portable internal walls. The internal space can be customized with lightweight and portable wooden frame for multiple functions.

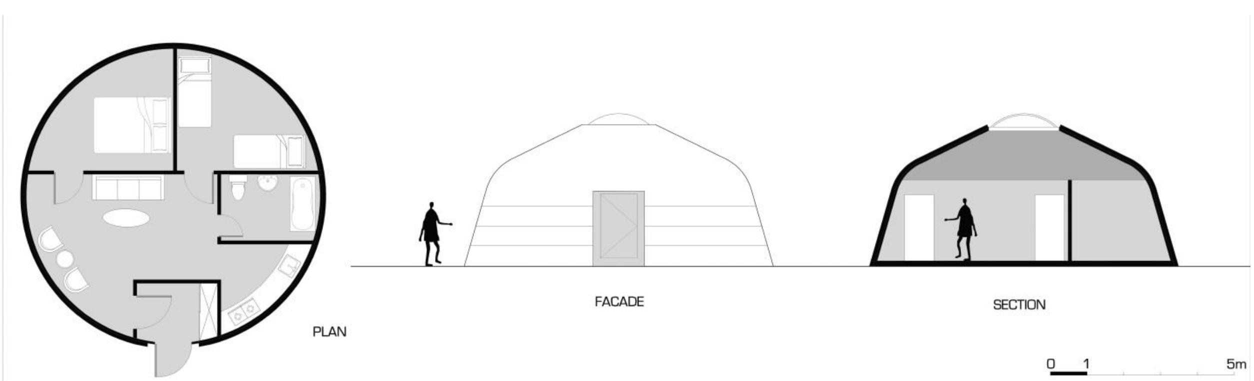


Figure 69: Drawing of the developed yurt with plan, façade, and section. (Family yurt-2).

6.4. Comparison of the existing, combined and developed yurts

The system energy comparison on existing yurt, combined yurt, and developed yurt are shown in Figure 70. The system energy of developed yurt is slightly lesser than the combined yurt and three times lesser than the existing yurt. The cooling energy consumes the smallest energy in total energy.

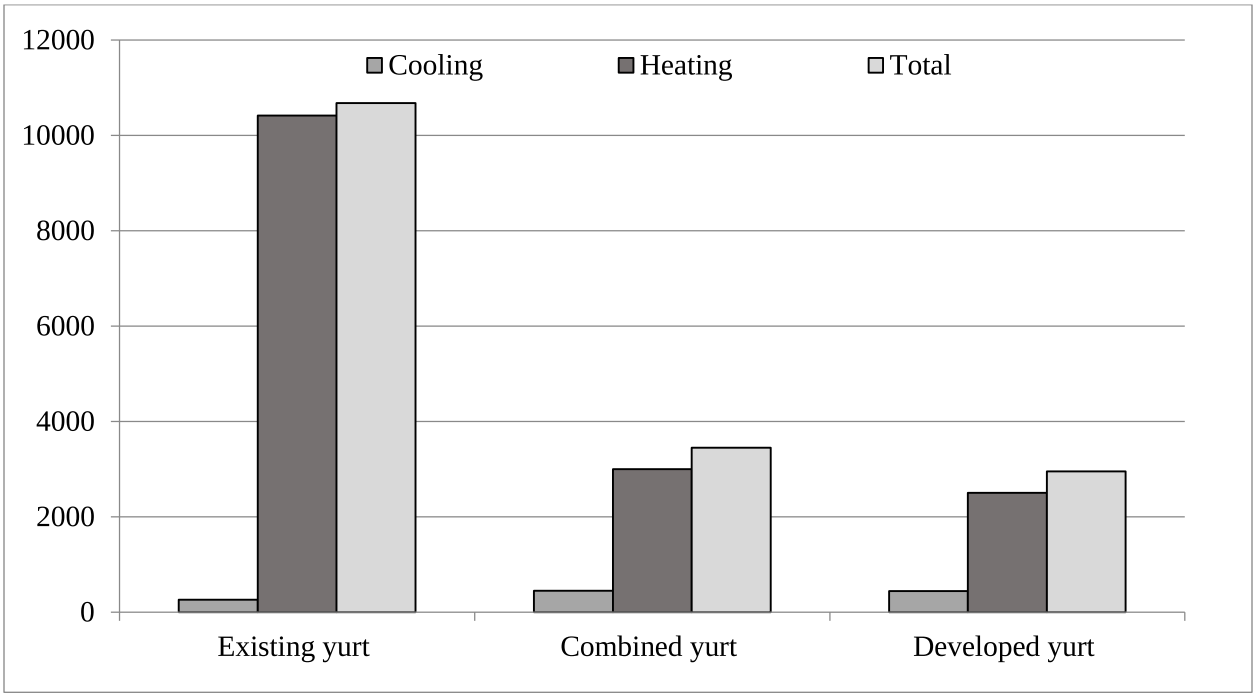


Figure 70: Comparison of the existing yurt, combined yurt and developed yurt with system energy.

In*Figure 71* illustrates the delivered energy comparison result on combined and developed yurt which has 50% lesser energy consumption than the existing yurt. Lighting and equipment, tenant energy are provided the same results for all yurts. Combined and Developed yurt's delivered energy consumption is including the AHU energy. The traditional existing yurt does not have AHU and only natural ventilation through the top opening and 'khayaa'. In this condition, if the top opening is closed CO_2 level is increased to very high amount. The mechanical ventilation of 'combined' and 'developed' yurt supports indoor air quality exchange and supports the cooling and heating.

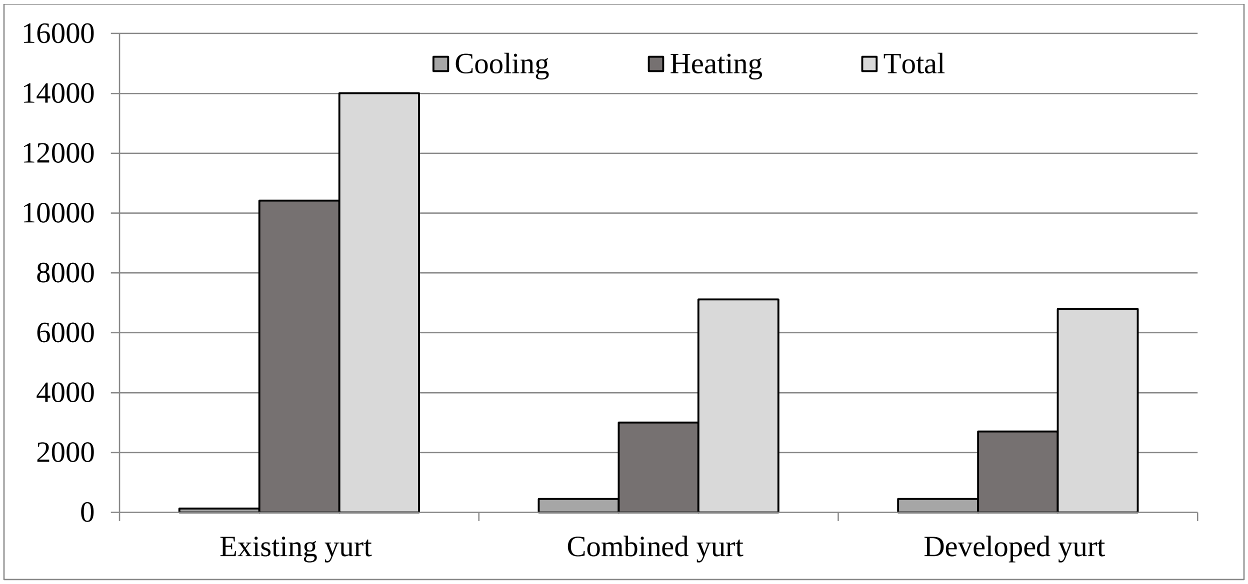


Figure 71: Comparison of the existing yurt, combined yurt and developed yurt with delivered energy.

In*Figure 72*illustrates the thermal comfort comparison between the existing yurt, combined yurt and developed yurt. The combined yurt thermal comfort is 12 times better than the existing yurt in terms of unacceptable numbers of occupancy hour. The developed yurt has 2 occupancy hours unacceptable category and the best category has much higher occupancy hours than other two yurts.

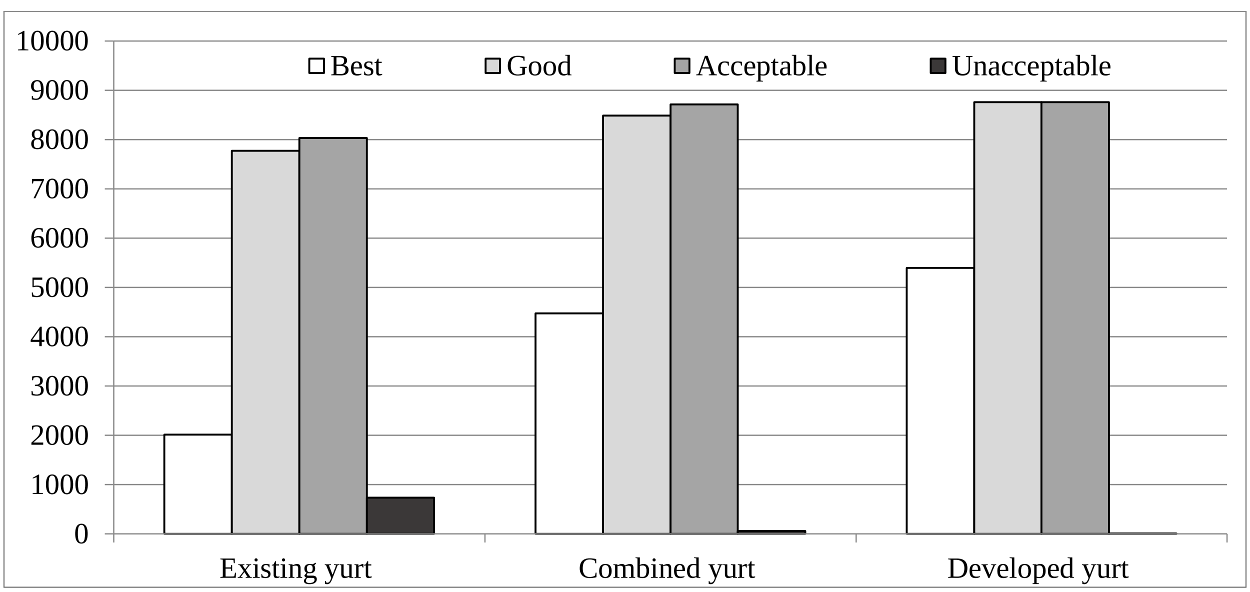


*Figure72***:** *Thermal comfort comparison of the existing yurt, combined yurt,and developed yurt.*

In Figure 73 illustrates a comparison of Fanger's comfort indicated with PMV for existing yurt (a), combined yurt (b), and developed yurt (c). Developed yurt PMV ranges between -0.8 and 0.3, which is close to the standard (DIN EN ISO 7730).

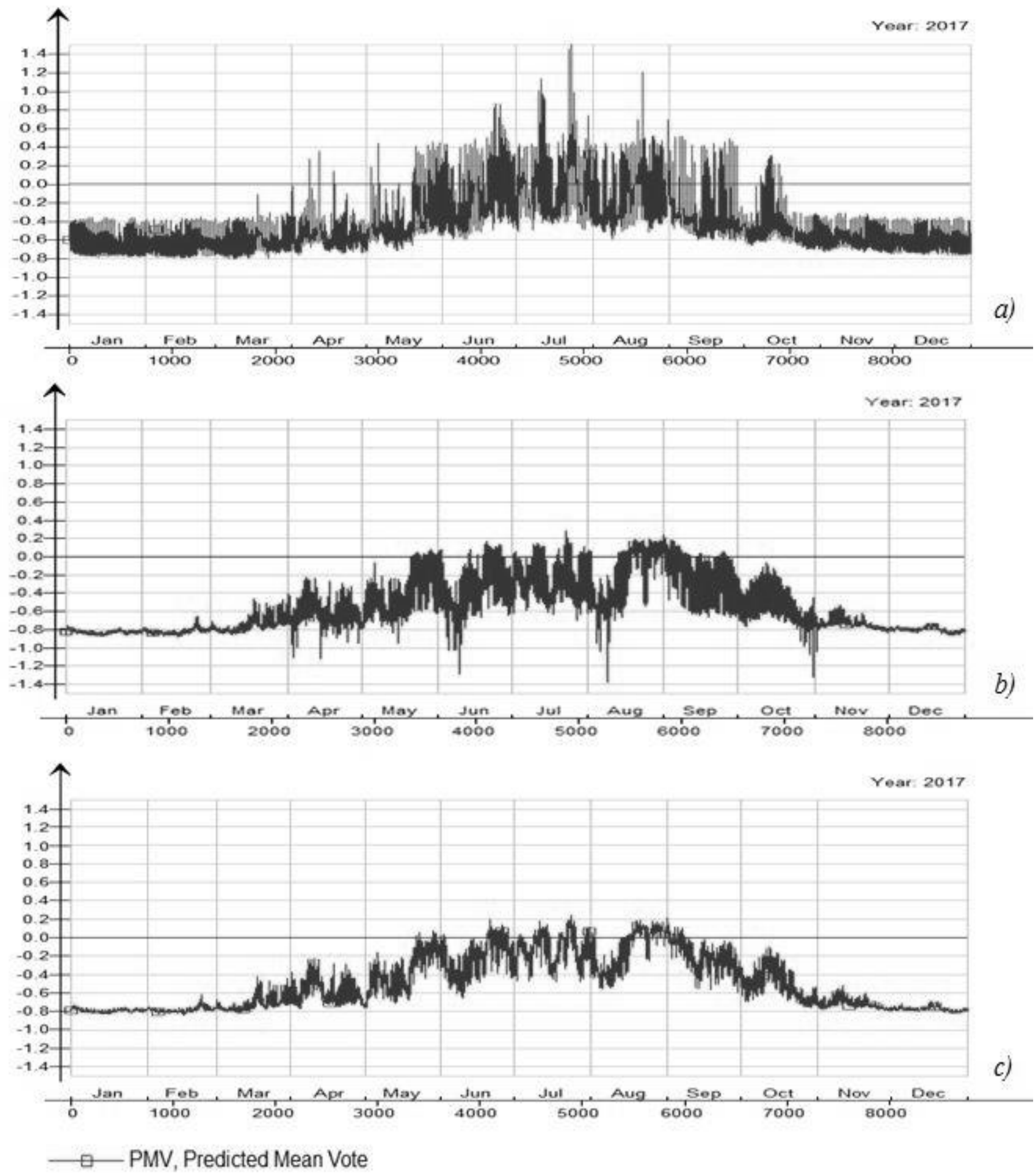


Figure 73: Comparison of the PMV. a) Existing yurt b) Combined yurt c) Developed yurt

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6.5. Conclusions: Optimized combination of an energy positive modern yurt prototype

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 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 are useful for all function of usages.

Combined yurt

The combined yurt has collected the all best characters including opening, orientation, structural material, and system. The characters are simulated, compared and optimized in Chapter 5.

It is investigated that the combined yurt is energy efficient and provides the indoor comfort. The combined yurt's energy consumption is 50% lesser than a traditional existing yurt.

The unacceptable category of combined yurt is 12 times lesser than the existing yurt in the thermal comfort result.

Indoor air quality is improved through the natural and mechanical ventilation system and it fulfills air quality acceptable level as indicated by CO_2 level.

Developed yurt

The combined yurt is further improved to design 'developed yurt' and improvements have done in interior and exterior of yurt. The interior is divided by rooms which make the yurt more functional and enables manageable operationalization. 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 fulfills the modern lifestyle. And the airlock space is designed which is connected to the entrance. The airlock reduces the heat loss from the door area.

In relation to interior space is divided into rooms, the exterior is re-designed with setting small windows which improves daylighting, visual comfort, and natural ventilation. The small windows can be set on outside of the flexible wooden wall and it should be highly insulated window with heat protection glass and orientation of window should be optimized.

The energy consumption of the developed yurt shows slightly more energy efficiency than the combined yurt from the simulation. In terms of thermal comfort, developed yurt is better than the combined yurt indicated in occupancy hours of the unacceptable category. Also, the PMV of developed yurt shows better results than combined and existing yurt.

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 for 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 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 4.8is 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.

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

- *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 simulation, 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 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**.**
- Possibility of replacing the top opening with a window would be preferable.

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

- *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 "The energy consumption and indoor comfort of the Mongolian traditional yurts in Mongolian climate", Proceeding of the Mongolian Academy of science, Mongolia, 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 glazing shows 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 case of window setting, it is better to be as small as possible.
- The orientation of the yurts did not show high effect 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 radiator and simple fan coil are 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.

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 50% 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 a 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 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 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 earth. And the inside air flow is very important for natural ventilation.

List of Publications by Tsovoodavaa Gantumur
Information as of October 30, 2018

Published:

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. 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

3. Importance of developing Ulaanbaatar regional forsite 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

4. 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

Submitted:

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

Author: Gantumur Tsovoodavaa, István Kistelegdi
Journal: Pollack Periodica (Submitted: 10 July 2018), Hungary

6. The energy consumption and indoor comfort of the Mongolian traditional yurts in Mongolian climate

Author: Gantumur Tsovoodavaa
Journal: Proceeding of the Mongolian Academy of science (Submitted: 27 July 2018), Mongolia

Published in conference proceeding:

7. 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)*

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

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

9. Review and systemization of the traditional yurt

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

10. 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)*

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

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

REFERENCE

[1] Anderson, Kjell. *Design energy simulation for architects: Guide to 3D graphics*. Routledge, 2014.

[2] Sovacool, Benjamin K., Anthony L. D'Agostino, and Malavika Jain Bambawale. "Gers gone wired: lessons from the renewable energy and rural electricity access project (REAP) in Mongolia." *Energy for Sustainable Development* 15.1 (2011): 32-40.

[3] Baabar, B. "From world power to Soviet satellite: History of Mongolia." *Cambridge: Cambridge University* (1999).

[4] Sneath, David, and Christopher Kaplonski, eds. *The History of Mongolia (3 Vols.)*. Vol. 1. Global Oriental, 2010.

[5] Miller, Bryan K. "Power politics in the Xiongnu empire." (2009).

[6] Barfield, Thomas J. "The shadow empires: Imperial state formation along the Chinese-nomad frontier." *Empires: perspectives from archaeology and history* 122 (2001): 10.

[7] Di Cosmo, Nicola. "Ethnogenesis, coevolution and political morphology of the earliest steppe empire: The Xiongnu question revisited." *Xiongnu Archaeology: Multidisciplinary perspectives of the first steppe empire in Inner Asia* (2011): 35-48.

[8] Manalsuren, Saranzaya. *An ethnographic investigation into Mongolian management in the context of cultural and institutional changes*. Diss. University of Essex, 2017.

[9] Hart-Davis, Adam, ed. *History: The Definitive Visual Guide: from the Dawn of Civilization to the Present Day*. Dorling Kindersley, 2013.

[10] Daajav B. *Yurt as the origin of Mongolian architecture*, (in Mongolian) Ulaanbaatar, Mongolia, Translated, 2006.

[11] Altangerel, Munhtuya, ed. *Modern Mongolia: Reclaiming Genghis Khan;[an Exhibition*. University of Pennsylvania Museum of Archaeology and Anthropology, 2001.

[12] Morgan, David. "The Mongols. The Peoples of Europe." (1986).

[13] Khan, Almaz, and Khubilai Khan. "The Mongols." *State, Ethnicity and the Politics of Representation in the PRC." Negotiating Ethnicities in China and Taiwan. Berkeley: Institute of East Asian Studies, University of California* (1996): 125-59.

[14] Urandchimeg.B, Rise, change and approach of the population, Ulaanbaatar, Mongolia, National Statistic Office of Mongolia, 2017.

[15] 2015 population and housing by-census of Mongolia: National report, Ulaanbaatar, Mongolia: National Statistic Office of Mongolia, 2015.

[16] Liedl, Petra, Gerhard Hausladen, and Michael Saldanha. *Building to Suit the Climate: A Handbook*. Walter de Gruyter, 2012.

[17] Batima, Punsalmaa, et al. "Observed climate change in Mongolia." *Assess Imp Adapt Clim Change Work Pap* 12 (2005): 1-26.

[18] Ministry of Tourism and Environment. (Japan), Climate change in Mongolia, Tokyo, Japan: Outputs from GCM, 2014.

[19] Dagvadorj, Damdin, et al. *MARCC 2009: Mongolia assessment report on climate change 2009*. 2009.

[20] Report on the state of the environment of Mongolia 2008-2010, Ulaanbaatar, Mongolia, 2011.

[21] Mongolian building standard, Standard of the building for urban planning 30.01.04, Ulaanbaatar, Mongolia: 2004

[22] Remund, Jan. "Accuracy of Meteonorm 7." *A detailed look at the model steps and uncertainties.[online] Available at: http://www. meteonorm. com/images/uploads/downloads/Accuracy_of_Meteonorm_7. p df [Accessed 21 Apr. 2016]* (2015).
[23] King, Paul. *The complete Yurt handbook*. Eco-logic books, 2001.
[24] Kemery, Becky. *Yurts: Living in the round*. Gibbs Smith, 2006.
[25] Bayarsaihan.B, Put up a Ger, Ulaanbaatar, Mongolia, 2006
[26] D. Bat-Ulzii.B, Encyclopaedia of the ger, the dwelling house of Mongols, Ulaanbaatar, Mongolia, 2016.
[27] GAO, Xiao-Xia, Hong-Cui ZHENG, and Guang JIN. "GREEN DESIGN PROPERTY OF MONGOLIAN YURTS [J]." *Journal of Inner Mongolia Agricultural University (Natural Science Edition)* 1 (2009): 023
[28] GUAN, Xiao-wu, and Di LI. "An Investigation on the Techniques and Skills of Making Mongolia Yurts in the Zhenglan-qi Mongolia Yurts Factory [J]." *Journal of Guangxi University for Nationalities (Natural Science Edition)* 2 (2006): 010.
[29] Salvalai, Graziano, et al. "Architecture for refugees, resilience shelter project: A case study using recycled skis." *Procedia Engineering* 180 (2017): 1110-1120.
[30] Chong, Geon Chai. "A Study on Spatial Composition and Elements of Ger Architecture in Mongolia." *Journal of the Korean Institute of Rural Architecture* 16.1 (2014): 111-117
[31] Nikiforov, B. S., et al. "THE DESIGN OF MONGOLIAN YURTS (GÉR): GENESIS, TYPOLOGY, FRAME, AND MODULAR TECHNOLOGIES AND THEIR TRANSFORMATIONS." *Sciences of Europe* 11-1 (2017): 56-69.
[32] Liu H. Y., Li Z. M., Ko F. K. A fractional model for heat transfer in a Mongolian yurt, *Thermal Science*, Vol. 21, No. 4, 2017, pp. 1861–1866.
[33] ZHANG, Xin-Hong, and B. A. I. Yu-Tong. "Study on Mongolian Yurt Features and Its Environmentally Friendly Design." *DEStech Transactions on Materials Science and Engineering*icmsea_mce (2017).
[34] Nemcsics, Ákos. "Contribution to around church reconstructed from its foundation wall." *Pollack Periodica* 6.1 (2011): 87-98.
[35] Dupree L. *Afghanistan*, Princeton University Press, 1980
[36] Kuz′mina, Elena Efimovna. *The origin of the Indo-Iranians*. Vol. 3. Brill, 2007.
[37] Eiraji, Javad, and Shabnam Akbari Namdar. "Sustainable systems in Iranian traditional architecture." *Procedia Engineering* 21 (2011): 553-559
[38] Apak K. Modernization of the 'Yurt' tensile structure, *International Conference on Adaptable Building Structures*, Eindhoven, The Netherlands, 3-5 July 2006, Paper 10-295.
[39] U.S. Patent No. 15/295,654, Housing system, Barry R. M. 2015.
[40] Gorman, Michael John, ed. *Buckminster Fuller: designing for mobility*. Skira-Berenice, 2005
[41] Mrkonjic, Katarina. "Autonomous Lightweight Houses: Learning from Yurts." *PLEA2006–the 23rd Conference on Passive and Low Energy Architecture*. 2006.
[42] Ching, Francis DK, and Ian M. Shapiro. *Green building illustrated*. John Wiley & Sons, 2014.
[43] Hausladen, Gerhard. *Climate design: solutions for buildings that can do more with less technology*. Birkhauser, 2005.

[44] Bauer, Michael, Peter Mösle, and Michael Schwarz. *Green building: a guidebook for sustainable architecture*. Springer Science & Business Media, 2009.

[45] DIN, EN. "15251: 2007-08: Eingangsparameter für das Raumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden–Raumluftqualität." Temperatur, Licht und Akustik, 2007.

[46] DIN EN ISO 7730: 2006-05. "Ergonomie der thermischen Umgebung–Analytische Bestimmung und Interpretation der thermischen Behaglichkeit durch Berechnung des PMV-und des PPD-Indexes und Kriterien der lokalen thermischen Behaglichkeit."

[47] T. Mohammad, "A review of thermal comfort in building," *"A review of thermal comfort in buildings.,* vol. 26, no. 2013, pp. 201-215.

[48] Yang, Liu, Haiyan Yan, and Joseph C. Lam. "Thermal comfort and building energy consumption implications–a review." *Applied energy* 115 (2014): 164-173.

[49] "Standard, ASHRAE "Standard 55-2004." Thermal environmental conditions for human occupancy," pp. 9-11, 2004.

[50] Auliciems, Andris, and Steven V. Szokolay. "Thermal comfort." PLEA, 1997.

[51] Peeters, Leen, et al. "Thermal comfort in residential buildings: Comfort values and scales for building energy simulation." *Applied energy* 86.5 (2009): 772-780.

[52] Komoto, Keiichi, Namjil Enebish, and Jinsoo Song. "Very large-scale PV systems for North-East Asia: Preliminary project proposals for VLS-PV in the Mongolian Gobi desert." *Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th*. IEEE, 2013.

[53] Bogdanov, Dmitrii, and Christian Breyer. "North-East Asian Super Grid for 100% Renewable Energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options." *Energy Conversion and Management* 112 (2016): 176-190.

[54] Ozgur, Ugur Erman. "Review of the Energy Charter Treaty (ECT) Implementation in Selected Areas: Analysis on Issues Related to Competition Under the Energy Charter reaty." (2012).

[55] Tserenpurev, BAT-OYUN, Masato Shinoda, and Mitsuru Tsubo. "Effects of cloud, atmospheric water vapor, and dust on photosynthetically active radiation and total solar radiation in a Mongolian grassland." *干旱区科学* 4.4 (2012): 349-356.

[56] Laughton, Chris. *Solar domestic water heating: The Earthscan expert handbook for planning, design, and installation*. Routledge, 2010.

[57] Pagliaro, Mario, Rosaria Ciriminna, and Giovanni Palmisano. "Flexible solar cells." *ChemSusChem: Chemistry & Sustainability Energy & Materials* 1.11 (2008): 880-891.

[58] Radha, Chro Hama, and Istvan Kistelegdi. "Thermal performance analysis of Sabunkaran residential building typology." *Pollack Periodica* 12.2 (2017): 151-162.

[59] Europian standard, " CSN EN 13799, LPG equipment and accessories- Contents gauges for Liquefied Petroleum Gas (LPG) pressure vessels," 2014.

[60] Mongolian building standard, Climate and geophysical evidence of construction" CCM 23-01-09, Ulaanbaatar, Mongolia: Minister of Road, Transportation, Construction and Urban Development, 2009.

[61] Mongolian standard, "Technical condition of cover insulation material for the yurt, MNS 5801:2007", Ulaanbaatar, Mongolian, 2007.

[62] Ariunbold.L, Energy and thermal efficient insulation material Rockwool, Ulaanbaatar, Mongolia, 2009.

[63] Frydrych, Iwona, Wioletta Sybilska, and Małgorzata Wajszczyk. "Analysis of Selected Physical Properties of Membrane Fabrics Infl uencing the Utility Comfort of Clothing." *Fibres & Textiles in Eastern Europe* 17.6 (2009): 77.
[64] Domínguez-Muñoz, Fernando, et al. "Uncertainty in the thermal conductivity of insulation materials." *Energy and Buildings* 42.11 (2010): 2159-2168.
[65] Abdou, A., and I. Budaiwi. "The variation of thermal conductivity of fibrous insulation materials under different levels of moisture content." *Construction and Building materials* 43 (2013): 533-544.
[66] Bardy, Erik R., Joseph C. Mollendorf, and David R. Pendergast. "Thermal conductivity and compressive strain of aerogel insulation blankets under applied hydrostatic pressure." *Journal of Heat Transfer* 129.2 (2007): 232-235.
[67] Coffman, B. E., et al. "Aerogel blanket insulation materials for cryogenic applications." *AIP Conference Proceedings*. Vol. 1218. No. 1. AIP, 2010.
[68] Simmler, Hans, and Samuel Brunner. "Vacuum insulation panels for building application: Basic properties, aging mechanisms, and service life." *Energy and buildings* 37.11 (2005): 1122-1131.
[69] Jiřičková, Milena, et al. "Thermal conductivity of mineral wool materials partially saturated by water." *International journal of thermophysics* 27.4 (2006): 1214-1227.
[70] Liang, Yuying, et al. "Thermal performance and service life of vacuum insulation panels with aerogel composite cores." *Energy and Buildings* 154 (2017): 606-617.
[71] Nemcsics, Ákos. "Contribution to around church reconstructed from its foundation wall." *Pollack Periodica* 6.1 (2011): 87-98.
[72] Abdou, A., and I. Budaiwi. "The variation of thermal conductivity of fibrous insulation materials under different levels of moisture content." *Construction and Building materials* 43 (2013): 533-544.