Field study seeking for affordable measures to improve living environment of urban gers located in Ulaanbaatar, Mongolia

プレブ, ウエルン, ウジン

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Field study seeking affordable methods to improve the living environment of urban *gers* located in Ulaanbaatar, Mongolia

A thesis submitted to Kyushu University in partial fulfillment of the requirement for the degree of Doctor of Engineering (DR. ENG.)

Uelun-Ujin Purev

January 2022

Declaration

I, Uelun-Ujin Purev, hereby declare that this thesis titled "Field study seeking affordable methods to improve the living environment of urban *gers* located in Ulaanbaatar, Mongolia," submitted in partial fulfillment of the requirements for the degree of Doctoral of Engineering, (Dr. Eng.) is my original research work and all the materials that been used from other sources have been properly and fully acknowledged.

Uelun-Ujin Purev

January 2022

Abstract

In Ulaanbaatar, the capital of Mongolia, the rapid increase in population in recent years has resulted in a delay in the development of infrastructure, and as of 2010, only 32% of all households were living in apartments with adequate infrastructure, while the remainder were living in *ger* areas that lack public services such as water and sewage. The *ger* areas are predominantly located at the northern boundaries of Ulaanbaatar and consist of detached houses (called *baisins*) and *gers* that are built by the residents. A *ger* is a nomadic mobile home with a circular plan and wooden frame and is covered using wool felted sheets; despite its simple structure, currently, *gers* are widely occupied by urban dwellers in Ulaanbaatar. Meanwhile, Ulaanbaatar is also currently suffering from serious air pollution caused by combustion gases that are emitted from the coal stoves used in *baisins* and *gers*. Consequently, replacing coal stoves with clean electric heating systems is an urgent issue; however, if all households in the poorly insulated *gers* switched to electric heating, the electricity demand would significantly exceed the current capacity. To achieve a smooth transition from coal stoves to electric heaters to reduce air pollution, the heating load in *gers* must be reduced on a large scale, according to the income level of the residents.

With this background, this thesis presents a series of studies based on a detailed field survey of *gers* that are occupied by settlers in Ulaanbaatar to develop affordable retrofitting methods for improved insulation in *gers* in accordance with the local conditions; moreover, this research attempts to clarify the actual indoor thermal environment of *gers* based on field measurements in winter.

In Chapter 1, the background of this study, problems in rapid urbanization, and solid fuel use in Ulaanbaatar, Mongolia, are described, and the objectives and structure of this thesis are presented.

In Chapter 2, the results of a survey conducted on 49 *gers* and 67 *ger* residents in the *ger* district of Ulaanbaatar are reported. The results show that the design and materials used in the *gers* are highly standardized; moreover, although *gers* can be easily reused by replacing or transferring parts, the residents have minimal knowledge on the insulation properties of felt sheets. While 85% of the respondents positively rated the indoor thermal environment as comfortable, most respondents said that it was sometimes too hot or too cold in winter, indicating the occurrence of significant temporal fluctuations in the indoor temperature. Furthermore, the heat loss coefficients

of the *ger* envelope, which were estimated from the answers on coal consumption in the *ger*, were reported to be significantly high when compared to those of detached houses in Hokkaido, which is a cold region in Japan. In addition to the above aspects, a survey of the manufacturers and sellers of various components of the *ger* indicated that the price of a typical *ger* is 2.5 million Mongolian tugrik (MNT; approximately 150,000 Japanese yen), which is one-fortieth of the price of a multi-family apartment with an equivalent floor area; consequently, *gers* are considerably affordable for low-income households.

In Chapter 3, based on the results of the conducted survey, which is described in Chapter 2, the author describes the development and demonstration results of a retrofit method for improving *ger* insulation that can be implemented on a large scale. The method involves insulation panels, which are fabric-covered insulation material, that are attached to the inner surface of the *ger* envelope using ropes. The joints of the panels are attached using Velcro to prevent air leakage, which allows the occupants to easily remove/attach the panels. Moreover, a prefabricated windbreak was proposed to reduce the inflow of external air when the door is opened. Further, the author installed and tested the developed system in winter in a *ger* in Ulaanbaatar and collected feedback from the residents and local authorities.

Chapter 4 reports the results of indoor thermal environment measurements that were obtained over a period of 30 days in two *gers* during winter under normal living conditions. In the latter period of the measurement, one of the *gers* was equipped with the retrofitted insulation system, which is described in Chapter 3, and the coal stove was replaced by electric heaters. The results provide detailed characteristics of the spatiotemporal variability of the indoor air temperature in comparison with a baseline *ger* without the retrofitted insulation and using a coal stove for heating. In general, the room temperature in the *ger* varies significantly over time because of the doors are opened frequently for the use of outdoor toilets and the output of the stove is unstable; moreover, because of the low airtightness of the *ger* envelope, the vertical temperature difference in the room was also large, resulting in long periods outside the thermal comfort zone when the measured results were judged on the basis of indoor air temperature alone. Further, it is also shown that the large heating power of the stoves that are widely used in *gers* is essential to ensure thermal comfort by countering the weakness of the low insulation and airtightness of *gers*.

Chapter 5 provides an overview and findings of each chapter and outlines the challenges for future large-scale implementation of retrofits for improved insulation in urban *gers*.

In summary, this thesis aimed to address the problems in controlling the air temperature in urban *gers* in Ulaanbaatar and the issues of indoor air pollution caused by the usage of coal stoves through a detailed field survey, field measurements, and by proposing a new retrofitting system tailored to the local conditions of urban *gers*, which demonstrates a significant contribution to the field of building environment engineering.

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Chapter 1
Introduction

Globally, 56.2% of the population live in urban areas and this value is projected to increase up to 60% by 2030, particularly in developing countries (World Economic Forum)(United Nations). Rapid urbanization is usually accompanied by an influx of rural migrants to the urban periphery, resulting in unplanned residential districts including numerous low-quality houses with insufficient urban infrastructures. Such informal settlements often suffer from poverty, vulnerable housing, insufficient living area, polluted drinking water, and lack of access to modern sanitation facilities, causing a severe health hazard. Therefore, the United Nations Sustainable Development Goal number 11 has set a target of "Sustainable cities and communities," which aims to achieve adequate, safe, and affordable housing and essential services as well as the upgradation of slums.

Mongolia is a developing country located in the northern part of East Asia (Fig. 1.1), which has experienced rapid urbanization over the last 30 years after democratization and the abolishment of a law restricting rural-to-urban migration in 1990. The urban population of Mongolia was only approximately 20% of the total population in the 1950s (United Nations, 2014). However, the urban population in 2019 had increased up to 72.9%, which is higher than the Asian regional average (World Meters, 2019). Particularly, the population in Ulaanbaatar, which is the capital city of Mongolia, has increased significantly. From Fig. 1.2, it can be observed that the population of Ulaanbaatar increased from approximately 540,000 in 1989 to 1,400,000 in 2016, comprising approximately 46% of the population of the country (National Statistical Office of Mongolia, 2016b). During the urbanization of Ulaanbaatar, rural migrants created unique communities, known as *ger* districts, which include multiple *ger*s used as dwellings for urban residents (Byambadorj et al., 2011).

Fig. 1.1 Map of Asia

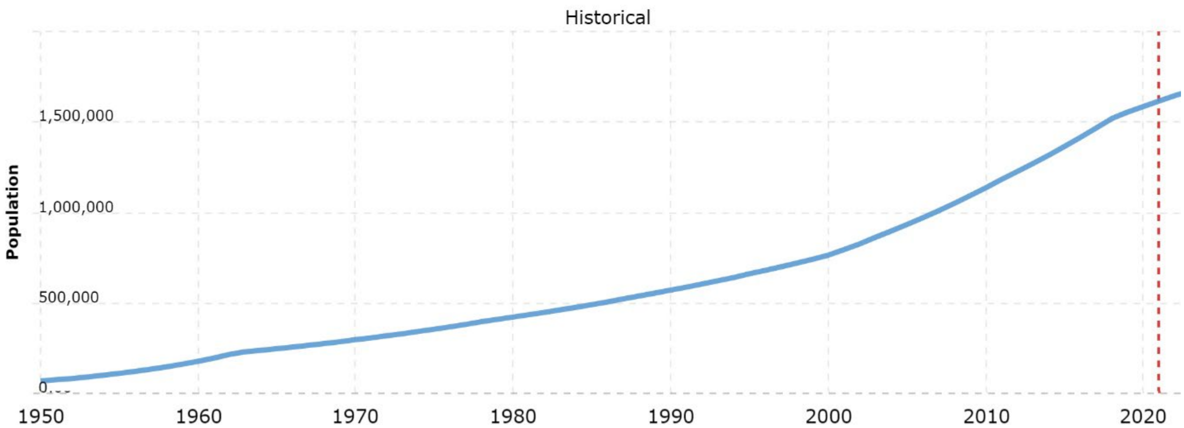

Fig. 1.2 Population of Ulaanbaatar 1950-2021 (United Nations - World Population Prospects)

The *ger* districts lack major infrastructures such as water, sewage, garbage collection, district heating systems, and qualified electricity connection. Moreover, Ulaanbaatar is one of the coldest cities with winter temperatures falling below −40 °C (National Climatic Data Center, 2017). Fig. 1.3 shows a climograph of Ulaanbaatar along with other major cities. Owing to the frigid winter season, as shown in Fig. 1.3, space heating is indispensable in Mongolia, attributing to 39.5% of the building energy consumption (Energy Charter Secretariat, 2011). Most of the detached houses located in *ger* districts are heated by coal-burning stoves, which is responsible for 80% of urban air pollution (Soluyanov, Gresch and Troyer, 2016). Consequently, Ulaanbaatar is one of the most polluted capital cities (UNICEF)(World Health Organization, 2018). Although various energy-efficient technologies related to space heating have been developed for energy saving and emission reduction worldwide, such technologies are not always affordable in most developing countries, such as Mongolia.

Under these circumstances, this study intended to seek affordable measures to reduce the pollutant emissions from traditional dwellings named *gers*, where 30% of the population of Ulaanbaatar reside.

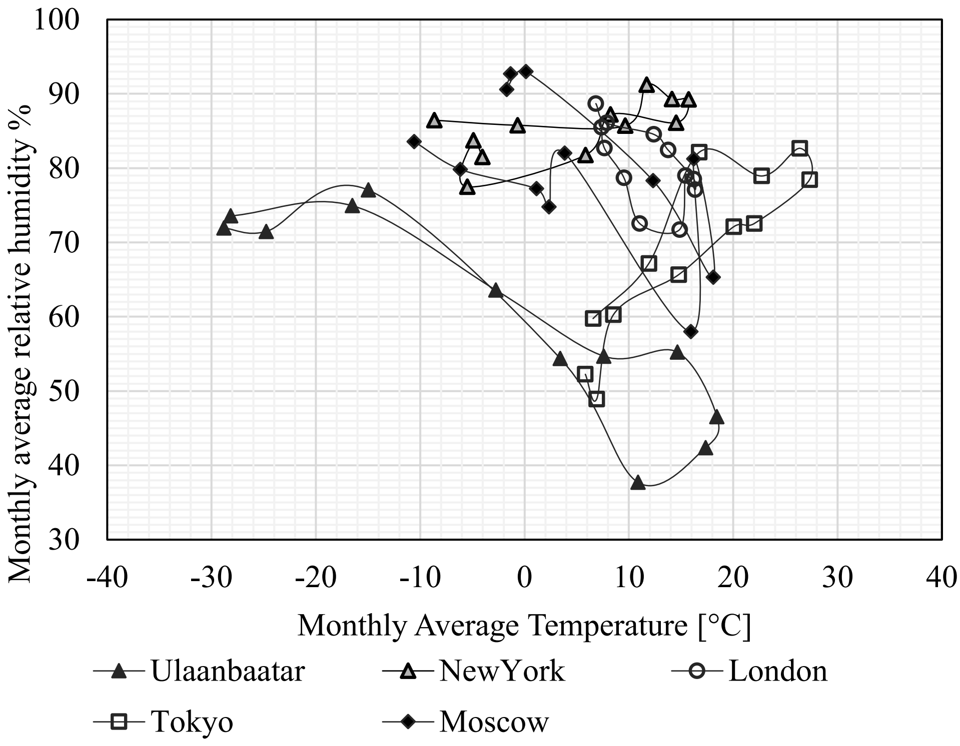

Fig. 1.3 Climograph of Ulaanbaatar and other major cities, (National Climatic Data Center, 2017)

1.1 Research background

1.1.1 Household fuel combustion

In 2012, the World Health Organization (WHO) reported that approximately three billion people in developing countries lack access to clean-energy services for cooking and heating, which results in indoor and outdoor air pollution (WHO, 2014). Air pollution is the existence of harmful matter that are detrimental to human health and the environment in the atmosphere. A previous study reported that indoor air pollution causes approximately 4.3 million premature deaths every year, particularly in developing countries, resulting in the death of 3.7 million people worldwide (Lancet, 2016). Approximately 90% of the world population breathes polluted air with air quality levels exceeding the limits set by the WHO (*Air pollution*). Fig. 1.4 illustrates the effects of solid fuel combustion on the environment and human health.

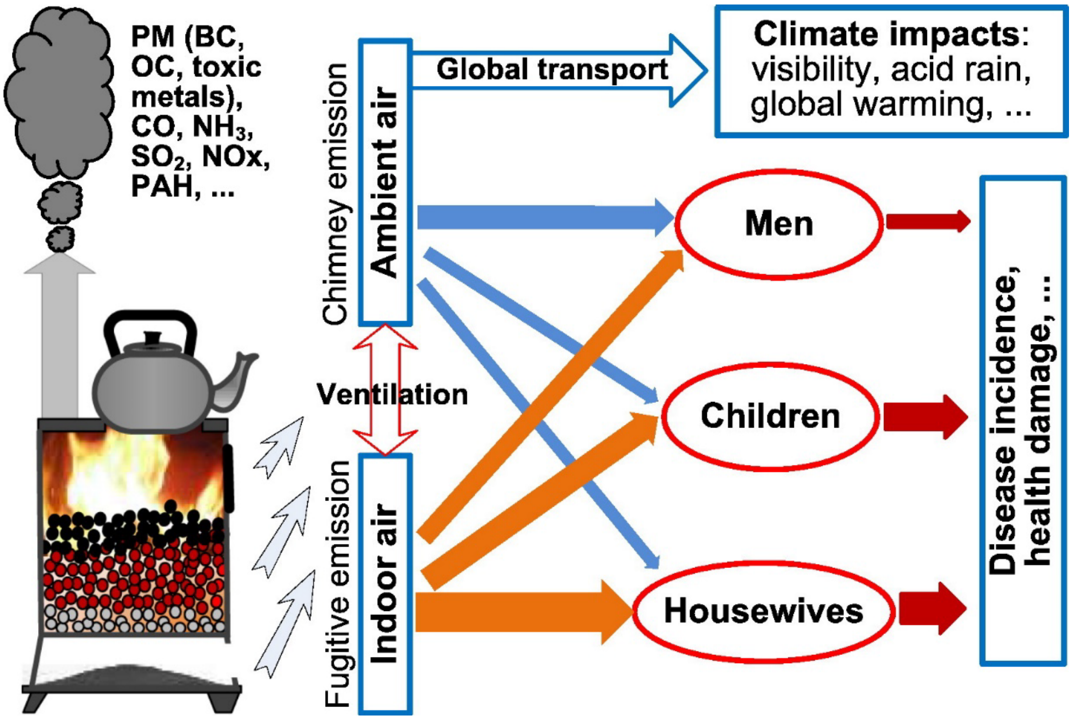

Fig. 1.4 Environmental and human health effects of solid fuel combustion (Li *et al.*, 2017)

Indoor air pollution is predominantly related to cooking and heating activities that require the burning of fuels such as dung, wood, and coal in developing countries. High levels of air pollution increase the risk of respiratory infections, heart diseases, and lung cancer. One of the most harmful pollutants is PM2.5 particles, i.e., particulate matter of diameter less than 2.5 µm, which can be inhaled deeply into lung tissue and contribute to serious health problems. Therefore, air pollution from household fuel combustion is recognized as one of the most important environmental health risks today. Thus, the WHO established a guideline for household fuel combustion (WHO, 2014), which strongly recommends that the usage of coal should be avoided. Moreover, the energy usage of such a household is associated with a high risk of burn injuries. To reduce such health risks, the WHO emphasized the necessity for countermeasures to mitigate the effects of solid fuel stoves and provided guidelines for different pollutants (WHO, 2014). Moreover, in developing countries, the exposure of families to indoor air pollution due to solid fuel combustion usually exceeds the limits specified in the WHO guidelines, triggering health problems for the occupants. Rabha et al. (2018) measured the level of PM2.5 and PM10 emissions caused by the burning of wood in northeast India, which was more than 10 times that of liquefied petroleum gas (LPG) usage. Luo et al. (2021) observed cognitive decline among middle-aged and older adults who use solid fuel in China and revealed that solid fuel users exhibited worse cognitive functions than clean fuel users. This effect was particularly significant in women and people with only a primary-school education level.

Mongolia is one of the countries having a high number of solid fuel users in *ger* districts. *Ger* districts are created by nomadic migrants who have relocated from rural areas to urban outskirts and these migrants predominantly live in *gers* or *baishins*. The original *ger* is a nomadic housing that is created using wooden structures that are covered by felt sheets, whereas a *baishin* is a self-built detached house. The indoor space in both *gers* and *baishin*s is currently heated by coal-burning stoves and these dwelling spaces do not have a plumbing or central heating system; therefore, occupants are exposed to significant amounts of pollutant emission from coal-burning stoves.

In winter, the outdoor air pollution in Ulaanbaatar is one of the worst globally and the daily average PM2.5 pollution level is 27 times greater than the level recommended by the WHO in 2014 (Fig. 1.5) (UNICEF, Soluyanov et al., 2016, Allen *et al.*, 2013).

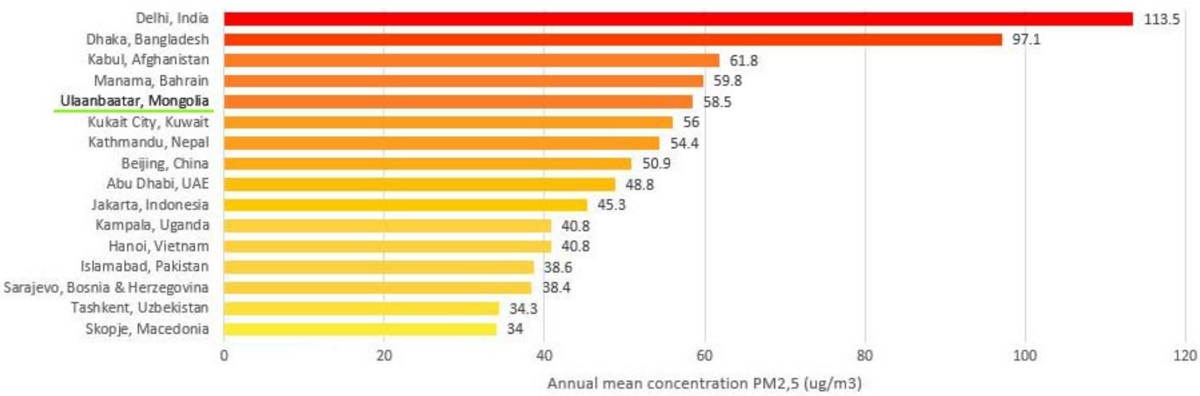

Fig. 1.5 Most polluted capital cities of the world (WHO, 2018)

In Mongolia, respiratory disease is the fifth leading cause of death among children aged 0–19 years (“Impact of Improved Stoves on Indoor Air Quality in Ulaanbaatar, Mongolia”). Chen et al. (2015) examined the urinary 1-hydroxyperene level of children aged 11–15 years in Ulaanbaatar and revealed that the 1-hydroxyperene level of children living in *ger* areas was 1.27 times higher than that of children living in non-*ger* areas. Nakao et al. (2017) reported that, in winter, people with ventilatory impairments who live in houses with smoke-rich fuel exhibited low health-related quality of life. Gombojav (2004) measured the indoor air pollutants of various housing units in Ulaanbaatar and reported that the mean concentration of carbon monoxide and particulate matter in *gers* and *baishins* were 1.65–1.89 and 1.2–2.37 times higher, respectively, than the levels in modern apartments. Otgonbayar et al. (2013) evaluated the impact of improved and conventional stoves on indoor air quality. At both *gers* and *baishins*, the indoor air particle quantities of PM2.5 and PM10 were higher than the indoor air quality standards specified in the Mongolian National Air Quality Standard (MNS) 4585-2007 (*Air quality MNS 4585 :2007*).

1.1.2 Actions to shift clean energy

During the last several decades, several households have shifted their space heating systems from solid fuel to modern fuels such as LPG and electricity in various countries, and the percentage of households relying on solid fuel at the global level has gradually decreased from 62% in 1980 to 41% in 2010. However, owing to the global population increase, the number of solid fuel consumers has remained unchanged at three billion users over the same period (Bonjour *et al.*, 2013). For shifting to clean energy, certain countries have introduced national programs, such as the program implemented by Indonesia to shift 40 million households from kerosine to LPG (Thoday *et al.*, 2018).

Based on a survey conducted by the Japan International Cooperation Agency (JICA) (2009) the Ulaanbaatar City Urban Development Policy Bureau developed the Ulaanbaatar City Master Plan 2030 (Law of Mongolia, 2015) in 2013. This master plan includes *ger*-district redevelopment projects to utilize household lands to build adequate high-rise, effectively insulated apartments with suitable infrastructure such as district heating. Enkhjargal and Nishikizawa (2012) studied the environmental and social impacts of the City Master Plan. Boldbaatar et al. (2017) interviewed 500 redevelopment project participants, reporting that their evaluation of the project was high. However, this project will required considerable time to redevelop all the *ger* districts in Ulaanbaatar. Therefore, in addition to this urban redevelopment project, replacing current coal stoves with energy-efficient clean-energy heating devices is important. To facilitate the replacement of conventional heating devices with clean-energy heating devices, the thermal performance of dwelling envelopes in current *ger* districts should also be improved.

To reduce pollutant emissions from stoves, the Mongolian government distributed more than 40,000 fuel-efficient stoves to households in the *ger* districts with a 50–90% subsidy between 2011 and 2015 with the support of the World Bank for replacing conventional stoves (Ulaanbaatar Services Improvement Project, 2015). In the improved stoves that were distributed, wood could be placed on the coal fuel, which allowed the updraft of the incomplete combustion gases and particle matter to pass through the flame of the burning wood, thereby reducing the emission of air pollutants. Moreover, to increase the usage of electric heaters, the Ulaanbaatar city government has implemented nighttime electric subsidies in *ger* districts during the heating season since 2017 (Ulaanbaatar Electricity Distribution Network, 2019).

1.1.3 Previous studies related to *ger* districts and urban *gers*

Mongolia has a long history of nomadic culture in harsh cold climate conditions, which has resulted in a unique urban formation that includes the *ger* districts. However, the capital city, Ulaanbaatar, is facing an environmental problem. *Ger* districts have been created by the movement of nomadic migrants to urban areas. Currently, 58% of households in Ulaanbaatar live in this area. Yatsuo (2016) indicated that the current condition of the *ger* districts can be perceived as a transition from the nomadic migration culture to a settlement culture in Mongolia. The expansion of *ger* districts from 1998 to 2012(Ochirbat, 2013) is shown in Fig. 1.6. Park et al. (2019) outlined that the area of *ger* districts increased from 32.15 to 221.15 km^2 between 1990 and 2013. Fig. 1.7 shows the breakdown of the different types of accommodation in Ulaanbaatar. The National Statistics Office of Mongolia (2016) reported that the ratio of families living in apartments that are connected to public infrastructure increased from 32% in 2010 to 41% in 2015. This might be partly because of the government-sponsored low-interest apartment project that was implemented for low-income households. Meanwhile, the households living in *gers* increased from 87,000 to 114,000 during this period because of increased migration to urban areas. Although *ger* districts exhibit the history of the urban formation of Ulaanbaatar, this area is currently recognized as a major source of air pollution in winter due to use of primitive coal stoves. Coal stoves in *ger* districts account for 80% of the total emissions in Ulaanbaatar; therefore, prompt actions for decreasing the heating load of buildings and transitioning from current coal stoves to heating appliances with low pollutant emissions in the *ger* districts are urgently needed to solve the current air pollution in the short term.

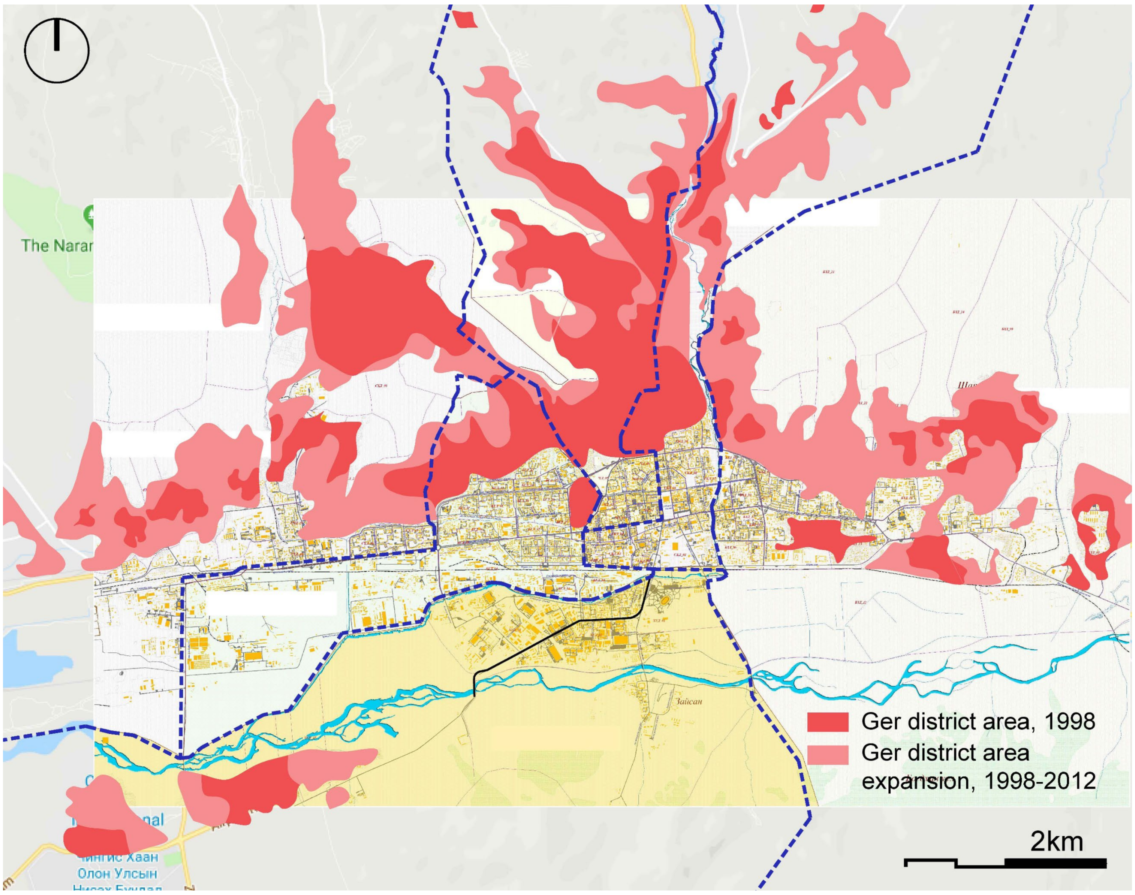

Fig. 1.6 Map of *ger* districts in Ulaanbaatar in 1998 and 2012. Obtained from Ochirbat (Ochirbat, 2013) and modified by the authors.

Fig. 1.7 Breakdown of the different types of accommodations in Ulaanbaatar (National Statistical Office of Mongolia, 2016b)

Therefore, various studies have been conducted to determine the current condition of *ger* districts. Otgonbayar et al. (2013) conducted a cost-benefit analysis targeting *baishin*s located in the *ger* districts based on the following three options: 1) replacement of conventional coal stoves with fuel-efficient coal stoves with low emissions, 2) replacement of coal stoves with heaters that use electricity generated by wind power, and 3) relocation from *baishins* to apartments with efficient insulation performance. They indicated that the first option has the highest cost-benefit performance. Conversely, Erdenedavaa et al. (2018) evaluated the applicability of solar collectors for space heating based on the field measurement of a simple detached house equipped with solar collectors, an electric heating system, and a coal stove in Ulaanbaatar. This study clarified the effectiveness of the solar thermal system even in the harsh and cold climate of Ulaanbaatar. Pillarisetti et al. (2019) observed the effectiveness and performance of electric heat pumps in *baishin*s and *ger*s during the winter season in Ulaanbaatar. Although a frigid climate generally decreases the performance of heat pumps for space heating, long-term field observations of their use in *baishins* and *gers* where people stayed with their usual living style showed acceptably moderate performance and considerably cheaper electricity consumption than coal consumption.

However, only limited research has been conducted on the thermal performance of *gers* in the *ger* districts. Ishikawa et al. (2007) conducted a field measurement on six *gers* in Ulaanbaatar and measured the indoor air temperature at different heights in the room. The measurement results indicated a large vertical distribution of indoor air temperature due to the poor insulation of the *ger* envelope. Buyantogtokh and Zang (2019) measured the indoor thermal conditions of 10 *ger*s. They indicated that the thermal environment of *gers* is not comfortable when compared to that of apartments. Moreover, the ventilation rates in *gers* were estimated based on CO_2 concentration; the heat loss coefficients of the *ger* envelope were also estimated based on coal consumption in the *gers*. Tsovoodavaa and Kistelegdi (2019) estimated the heating and cooling load of nine types of *yurts* (*gers*), which are used worldwide, including in Mongolia, under the Mongolian climatic condition based on a building energy simulation. Tong et al. (2018) developed a simple numerical tool to estimate the reduction in coal consumption and carbon emission due to the retrofitting of *baishins* in Mongolia for improved insulation; the estimations were based on onsite measurements of 21 *baishins* and questionnaire-based interviews conducted with 124 participants.

Moreover, questionnaire-based surveys were also conducted to understand the living condition of *ger* residents in the *ger* districts. For example, Gonchigbat et al. (2016) conducted a field survey on the living environment of 100 families living in *ger*s located in the *ger* districts of Ulaanbaatar. Caldieron and Miller (2015) investigated residential satisfaction toward their living environment in *ger* districts of 112 households in Ulaanbaatar. This survey result indicated that 35% of surveyed households were satisfied or very satisfied, and 33% of the surveyed households felt neutral emotions regarding their current *gers*. Although the majority of families expressed satisfied or neutral emotions regarding their living environment, the same number of families also indicated their intention to move to an apartment with suitable facilities.

Furthermore, there is a lack of studies on the development of feasible measures to improve the current *ger* design while considering the conditions of income level and willingness of occupants to pay for the improvements in the *gers*. In line with this analysis, this study focused on urban *gers* in the *ger* districts, which are occupied by approximately 114,000 urban households in Ulaanbaatar according to data reported in 2015 (National Statistical Office of Mongolia, 2016b). Based on the knowledge related to building environmental engineering, improving the insulation performance of the building envelope and airtightness is theoretically a simple and common measure. However, such a simple measure is difficult to implement in developing countries such as Mongolia owing to financial limitations. Moreover, a *ger* is a nomadic dwelling unit that has a completely different structure when compared to modern architectures. Therefore, in this study the author developed a tailor-made insulation prototype based on a thorough investigation of the local conditions.

1.2 Research objectives

This study was intended to propose an affordable retrofitting method to improve the thermal environment of urban *gers* in Ulaanbaatar, Mongolia to reduce coal consumption in winter.

The research aimed to reduce emissions from coal stoves and improve the indoor and outdoor air quality of households in *ger* districts. The objectives of the present study are summarized as follows:

1. To comprehend the current living conditions of families residing in urban *gers* in Ulaanbaatar. Specifically, the design and materials of *gers*, living habits of occupants, space heating method, indoor thermal perception, and willingness of occupants to improve the current living condition of *gers* should be clarified.
2. To observe the current market trend, price of *gers*, and available insulation materials in a local market to seek affordable and efficient insulation methods for *gers*.
3. To develop a tailored insulation retrofitting method for standard urban *gers* and demonstrate it at a real site.
4. To understand the indoor thermal environment of urban *gers*, which are heated by a primitive coal stove in winter.
5. To investigate the thermal performance of the developed retrofitting method.

1.5 Outline of the thesis

This thesis consists of five chapters. A brief description of each chapter is listed as follows:

- **Chapter 1: Introduction** describes the background, purpose of the research, and a review of previous research. The major urban issue of indoor and outdoor air pollution due to household fuel combustion, its environmental and health issues, and the government actions are briefly described in the background of research and further research targets and previous research findings are explained. Finally, the objective of the research is briefly described.
- **Chapter 2: Field Survey on Urban *Ger* Housing** reveals the result of the field survey conducted on 49 urban *gers* and 67 *ger* residents in the *ger* district of Ulaanbaatar, Mongolia. The size of the *ger*, method of space heating, energy-use behavior of occupants, perception of indoor thermal condition during winter, and satisfaction of residents with their living condition were examined. Moreover, the operation of a major market that sells *gers* was observed to comprehend the prices and materials used in *gers*. This chapter intends to clarify the boundary conditions for establishing applicable

measures for the reduction of energy consumption and pollutant emissions as well as to improve the indoor thermal environment.

- **Chapter 3: Development of a Retrofitting Method for Improved Insulation in Urban *Gers*** briefly describes the method used to design an insulation prototype for *gers* and the manufacturing process to achieve the final product. The design of the insulation prototype was completely tailored to the measurements of a five-walled *ger,* and can be used for additional insulation. The insulation prototype can be attached on the inner side of an assembled *ger* and is removable. High-performance insulation materials that are available in the local market were used.
- **Chapter 4: Field Measurement of the Indoor Thermal Condition of Urban *Gers* in Winter** reports the three stages in the indoor thermal measurement of two *gers* in the *ger* district of Ulaanbaatar, Mongolia in winter. The indoor air temperature at different heights and positions, surface temperatures, and outdoor air temperature were measured for 30 days. The first measurement for a period of 10 days (Term 1) was conducted on two basic *gers* to observe the current indoor thermal environment due to primitive coal stove heating. The next measurement of 10 days (Term 2) was conducted after installing an insulation prototype in *ger* A; moreover, the coal stove was replaced by an electric heater to demonstrate the insulation prototype. Finally, measurements were conducted for 10 days (Term 3) after a windbreak room was attached to both *gers* to demonstrate its performance. To examine the thermal exposure of the occupants, mean radiant temperature (MRT) was calculated based on the surface temperature of the *ger* envelopes and the estimated radiation energy of the stove. The operative temperature was used to evaluate the current thermal condition of the *ger*.
- **Chapter 5: Conclusion and Recommendation** summarizes previous chapters and presents a recommendation based on the results of this study.

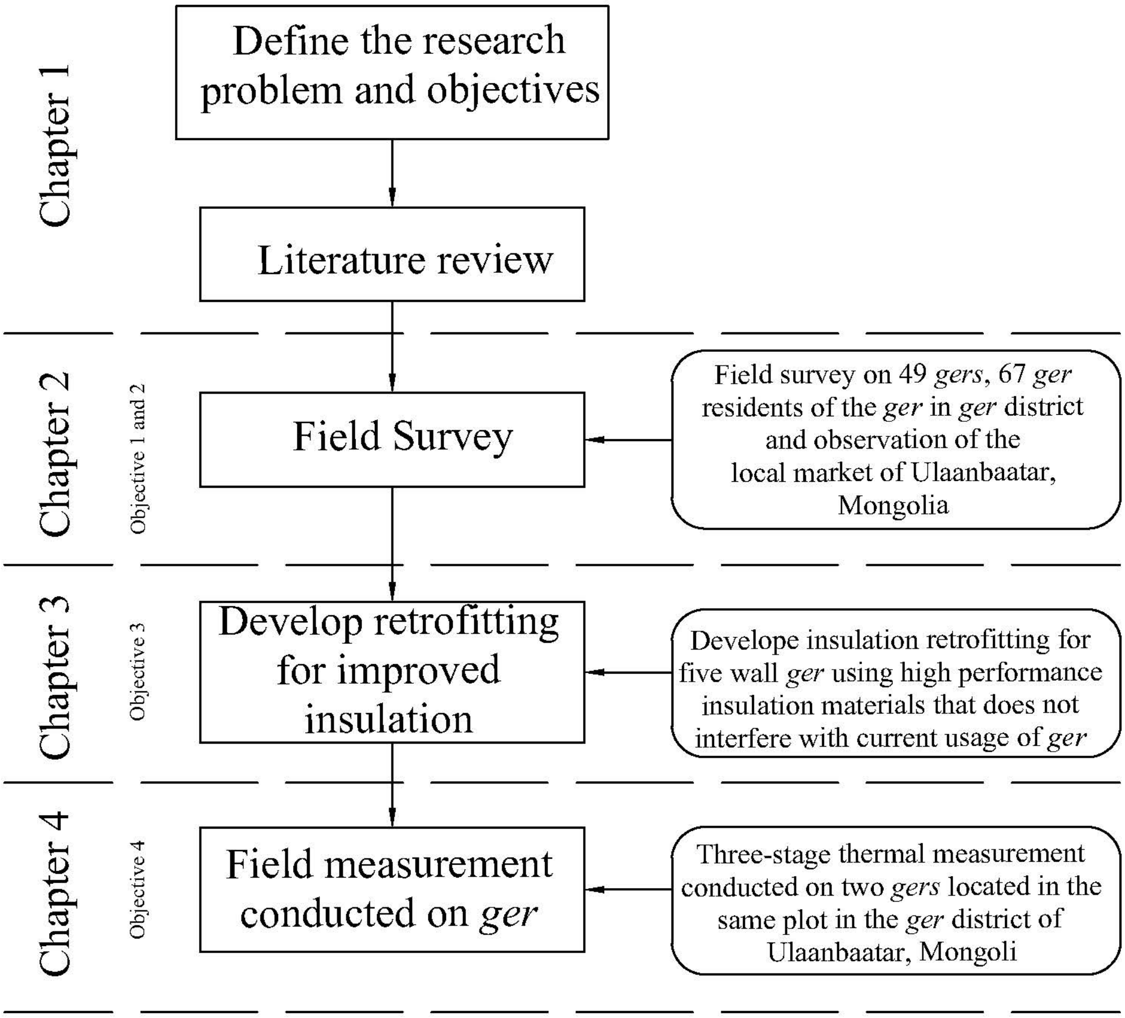

Fig. 1.8 Research Flow

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Chapter 2
Field Survey on Urban *Ger* Housing

2.1 Introduction

The *ger* is a nomadic cultural heritage that has been developed throughout the long history of Mongolia. The design, structure, and material of *gers* have been completely adjusted to a nomadic living style. However, during the rapid urbanization that has been occurring in Ulaanbaatar since 1970, numerous *gers* have been built by rural migrants moving to Ulaanbaatar, resulting in residential areas called *ger* districts. The *ger* districts generally lack urban infrastructures such as district heating systems, city water, sewage, and garbage collection. According to the National Statistics Office of Mongolia (2016), as of 2016, 58% of the families in Ulaanbaatar were living in the *ger* districts, of which 52% of the households were living in *gers* and the remaining 42% were living in self-build detached houses named *baishins*.

Meanwhile, Ulaanbaatar is suffering from severe air pollution, and the *ger* districts are responsible for 80% of pollutant emissions, which are caused by their use of primitive coal stoves for space heating (Soluyanov, Gresch and Troyer, 2016). Most of the *gers* and *baishins* in the *ger* districts are heated by coal stoves and have poor insulation performance, resulting in a significant energy consumption and pollutant emissions. Thus, the replacement of primitive coal stoves with clean heating devices with lesser emission and better energy efficiency is an urgent issue; however, resolving this issue is challenging owing to financial limitations. To facilitate switching from coal stoves to electric heaters, the Mongolian government have subsidized nighttime electricity price in *ger* districts since 2017 (Ulaanbaatar Electricity Distribution Network). Moreover, an insulation subsidy program for *baishins* was implemented in 2018 for an indefinite period (*Insulation solution project*). However, similar projects to improve the insulation performance of *ger* housing have never been conducted because of its unique features as a temporary housing design.

With this background, the objective of this chapter is to reveal the current characteristics of urban *ger* housing in terms of designs, materials, heating measures, and perception of residents toward their living environment. To achieve this, the author conducted field surveys in Ulaanbaatar. A description of the survey methodologies is presented in Section 2.2. Section 2.3 summarizes the observed characteristics of *ger*s and Section 2.4 describes the utilization of indoor space and space heating methods in different households. In Section 2.5, the potential countermeasures based on the survey results are discussed and Section 2.6 concludes the survey.

2.2 Outline of the field survey

2.2.1 Questionnaire-based survey of the residents of urban *gers*

The author conducted a survey on 49 families living in *gers* located at four different districts of Ulaanbaatar in August 2018. Seventy household members participated in the questionnaire survey that focused on their living style, demographic information, heating devices, behaviors related to energy use, coal usage, perception of indoor thermal conditions during winter, satisfaction with their living conditions, and willingness to improve the current living condition.

Thirty-seven questions were developed for the survey. The questionnaire-based survey consisted of two parts; the first part of the survey was directed at the head of the household head or a responsible member regarding basic data related to the *ger*, general information of the family, their living style, and type of space heating method that is used. The second part of the survey consisted of 21 questions for each household member and surveyed their indoor behaviors and their satisfaction with the thermal conditions of the *ger* in winter. The survey questions were not limited to only the prepared questionnaire; particularly, the interviewees were also encouraged to freely express their opinions, and based on their statements, the interviewers added questions about related issues, such as the way they defined insulation quality. The questionnaire sheets used for the interview are included in Appendix 1. Depending on the number of members in a household, the interview was conducted for approximately 20 min. The interviews were conducted in the Mongolian language and recorded for efficiency and accuracy.

Among the 70 respondents, the data of 67 respondents aged 15 and over were used for the subsequent analysis. In addition, the author also recorded the interiors and exteriors of 44 *gers* through photographs. Furthermore, the sizes of *gers* were measured using a laser meter with the permission of *ger* owner, which were obtained during the interviews. Two household heads agreed to participate in the interview, but prohibited the author from entering their premises. Moreover, three household members did not reside in the *ger* at the time of the interview. These household members were interviewed at their workplaces.

Table 2.1 lists the number of surveyed *gers* and the household members classified by the area. There are nine wards in Ulaanbaatar: three subwards and six pericentral wards. The pericentral wards are Bayangol, Bayanzürkh, Chingeltei, Khan-Uul, Songino Khairkhan, and Sükhbaatar;

the subwards are Bagakhangai, Baganuur and Nalaikh. According to a report in 2016 (Statistical Department of Ulaanbaatar, 2016), the proportion of households living in *ger* districts of each ward varies from 10 to 40%. The six pericentral wards are the most populous of the nine wards in the city; therefore, the survey was conducted in the *ger* districts located in four different pericentral wards: Bayangol, Chingeltei, Songino Khairkhan and Sükhbaatar. Songino Khairkhan has the highest number of households residing in a *ger* district (n = 31,338) (Statistical Department of Ulaanbaatar, 2016). The surveyed area in Bayangol is located downtown, within 3 km from City Hall. In contrast, the surveyed areas of Chingeltei and Sükhbaatar are located in a suburban residential zone.

The author primarily recruited respondents through a personal connection in Bayangol and Sükhbaatar districts. Households that had spent at least one entire winter in their *ger* were considered for the survey. Moreover, the author visited *gers* located in Songino Khairkhan and Chingeltei without an appointment and requested their cooperation in the survey if occupants had experienced at least one entire winter in the *ger*.

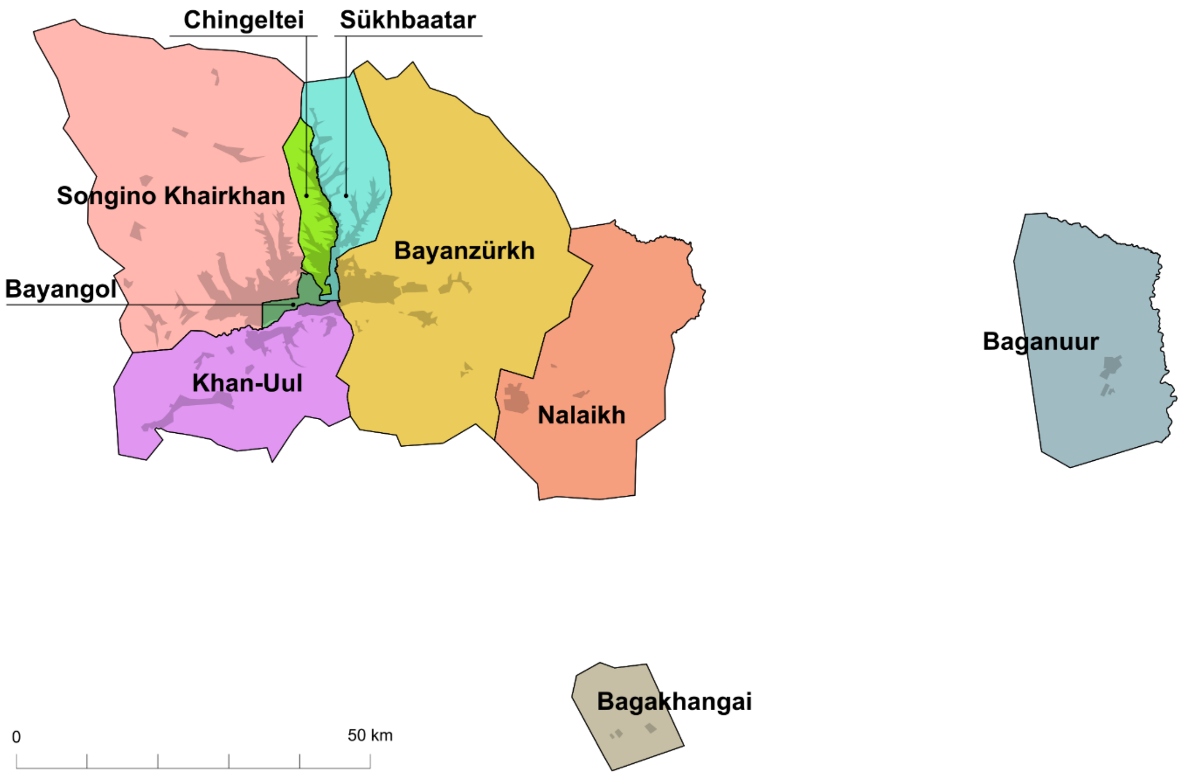

Fig. 2.1 Map of the districts in Ulaanbaatar (JICA, 2009)

2.2.2 Survey on the sales and manufacture of *gers*

The author visited the Naran Tüul Market in Bayanzürkh District, Ulaanbaatar, in August 2018, and surveyed the shops and stores that sell various parts of the *ger*. Narantuul is known as a central market and covers an area of 22.2 hectares; moreover, over 15,000 traders, producers, and service providers sell almost all types of products and services in this market. Fig. 2.2 shows some *ger* shops in the Narantuul market.

In this market, people can buy *ger*s and replacement parts. The author interviewed traders in nine shops: three felt sheet shops, three skeletal frame shops, and three shops selling packages with parts for assembling a complete *ger*. All these shops were managed by manufacturers. The traders in each shop was interviewed about various aspects such as the quality, price, and manufacturing techniques of different products. Furthermore, the authors visited two felt sheet manufacturing plants, one located at 19th *Khoroolol*, Khan-Uul district and the other at Salkhit, Chingeltei district, and observed the fabrication processes. Fig. 2.3 shows the felt manufacturing process at the aforementioned plant located in Salkhit.


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Fig. 2.2 *Ger* sales at the Narantuul market: (a), (b) images of shops selling *gers*; (c) sheets to decorate the interior wall of a *ger*; (d) rolled felt sheet; (e) cutting and stitching processes of a felt sheet, which is used as the roof of a *ger*, in the market

Fig. 2.3 Conventional felt manufacturing process

2.3. Results of the interviews conducted with the *ger* residents

2.3.1 Profile of surveyed *ger*s and households

Fig. 2.4 shows the distribution of the number of members in different households. The statistics of the entire Ulaanbaatar city (National Statistical Office of Mongolia, 2017) are included for reference. Although *gers* and households surveyed in this study were not chosen in a statistically random manner, the current data generally show a similar tendency to the data of the city, in which the most common size of household was four members. Nevertheless, the present data are marginally shifted toward households with a larger number of members when compared to the statistics.

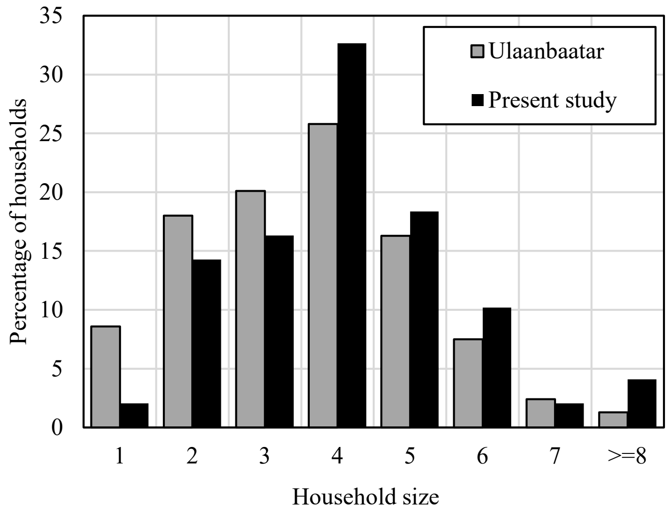


Fig. 2.4 Proportional distribution of household members in the sample and Ulaanbaatar [1]

Fig. 2.5 shows the number of employed household members corresponding to the household size in this survey. The results indicate that mid-sized households with four to five members tend to have one or two employed members, and the proportion of unemployed members increased with the household size. Fig. 2.6 shows the breakdown of the employment type of respondents classified by gender. The ratio of male respondents who are employed was two times higher than that of female respondents. Conversely, 30% of the employed female respondents were classified as being on maternity leave or being responsible for housework, indicating that they spent longer time at home.

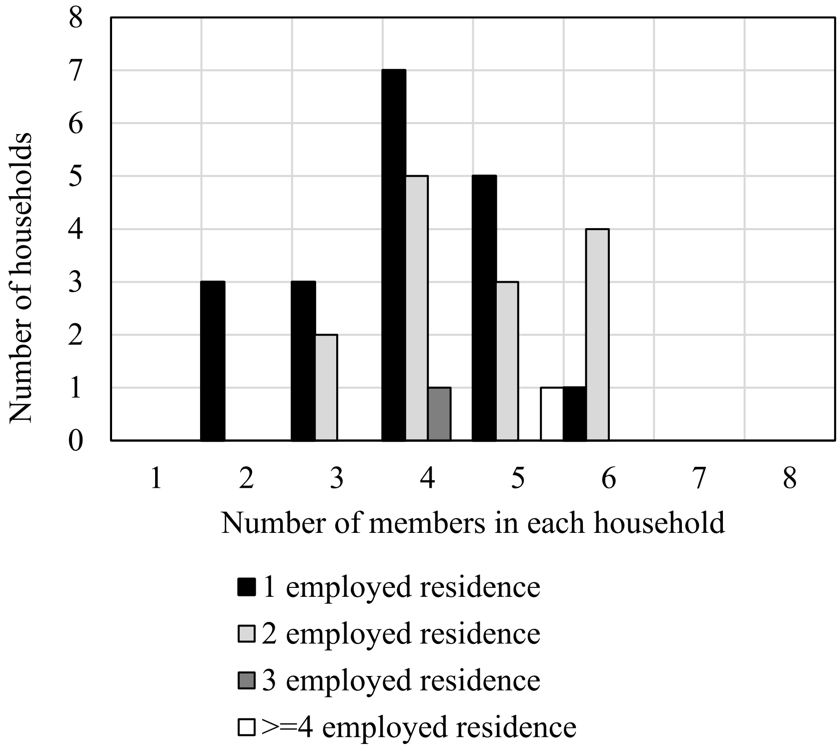


Fig. 2.5 Number of employed household members with respect to the household size

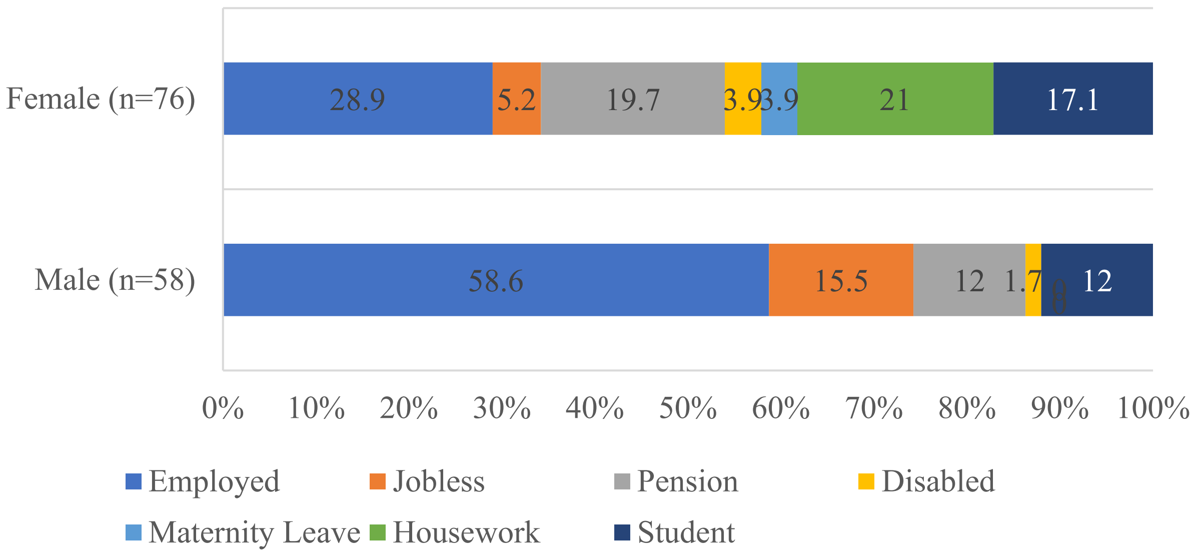


Fig. 2.6 Employment status of households members according to gender

Fig. 2.7 shows the distribution of the monthly household income of the samples. For reference, the national urban data in 2018 covering not only Ulaanbaatar but also other smaller cities (National Statistical Office of Mongolia, 2018) are also included. In this survey, the mean and median monthly household incomes were MNT 600,000 (US$ 215) and MNT 400,000 (US$ 140), respectively. In contrast, the mean and median monthly household incomes of the national urban data were MNT 1,100,000 (US$ 385) and MNT 1,000,000 (US$ 350), respectively. The increase in the national urban data is because it includes the data of families living in apartments and *baishins*.

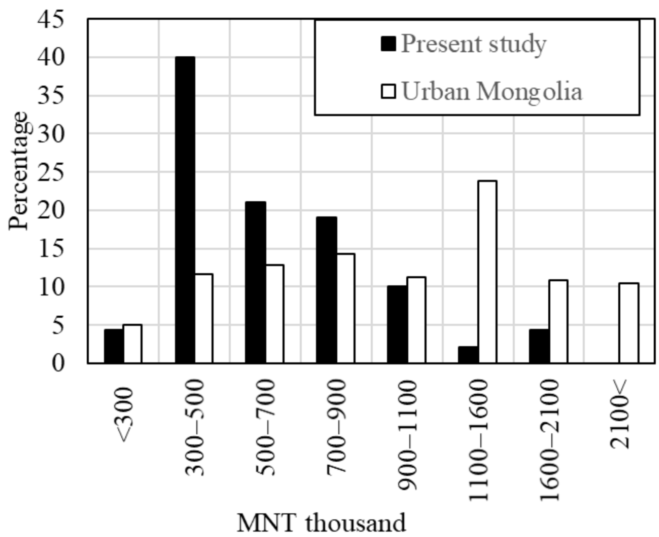


Fig. 2.7 Distribution of monthly household incomes in the sample (n = 49) and among the urban population of Mongolia (National Statistical Office of Mongolia, 2019)

2.3.2 Accessibility of infrastructure and public service of surveyed *gers*

Table 2.2 lists the accessibility of public infrastructure from the surveyed *gers*. Electricity and access to public transportation are available at all surveyed *gers*. In *ger* districts, owing to lack of infrastructure in terms of water supply and sewage system, the surveyed households need to transport water for daily use from a water kiosk by carriage or vehicle. Among the surveyed households, a water kiosk was accessible to forty families and eight households used water from a deep well. The average distance from a *ger* to a water kiosk from which people transported water on foot was 600 m; however, certain suburban districts have fewer water kiosks; consequently, five *gers* in these districts were located at a distance greater than 1 km from the water kiosk. The water kiosks are generally refilled by tanker trucks. In the case of kiosks that are located in downtown areas, the water is directly supplied through underground piping by a central water supply system. In certain suburban areas, deep-well kiosks were used for water supply. The National Statistics Office of Mongolia reported that 712 water kiosks existed in the *ger* districts of Ulaanbaatar in 2018 (National Statistical Office of Mongolia, 2019). The photograph of a water kiosk in a *ger* district is shown in Fig. 2.8.

All surveyed households were using outdoor toilets because sewerage sanitation systems were not provided in *ger* districts. Fig. 2.9 shows an outdoor toilet in a surveyed plot. The surveyed households had no bathing facilities; therefore, 98% of respondents used public bathhouses, which have recently become popular for people living in the *ger* districts. In 2019, Ulaanbaatar had 271 public bathhouses with a total capacity of 1,368 people (National Statistical Office of Mongolia, 2019).

This limited public water system is partly because of the significantly cold climate of Mongolia, which causes water to freeze up to considerable depths of approximately 2.6–3.8 m during winter (Ministry of Construction and Urban Development, 2016). Therefore, the construction and maintenance costs of public water supply systems are more expensive than those in other regions with moderate climatic conditions.

Moreover, the roads in *ger* districts are generally unpaved. Among the 49 households, only 1 family had a direct connection to a main road paved with asphalt. A photograph of an unpaved road in the surveyed district is shown in Fig. 2.10.

Table 2.2 Available and accessible infrastructure for surveyed *gers*

Infrastructure type	**Number of households**	**Percentage of households**
Bus station within 400 m	49	100 %
Direct connection with an asphalt road	1	2%
Facilities available in the premises		
Electricity	49	100 %
Playground for children	45	92%
Internet/WiFi	33	67.3%
Sewerage	0	0 %
Neighborhood facilities		
Water kiosk	40	81.6%
Deep well	8	16.3%
Playground area for children within 500 m	15	30.6%
Pharmacy	19	39%
Shopping center	33	67.3%
Hospital	33	67.3%
Kindergarten within 500 m	22	45%

Fig. 2.8 Water kiosk located at 19th *khoroo*, Chingeltei district. The photograph was captured by the author on November 03, 2018.

(c) Outdoor toilet

Fig. 2.9 Outdoor toilet at Gandan, Bayangol district. The photograph was captured by the author on August 15, 2018.

Fig. 2.10 Unpaved street at 7th *khoroo*, Chingeltei district. The photograph was captured by the author on August 17, 2018.

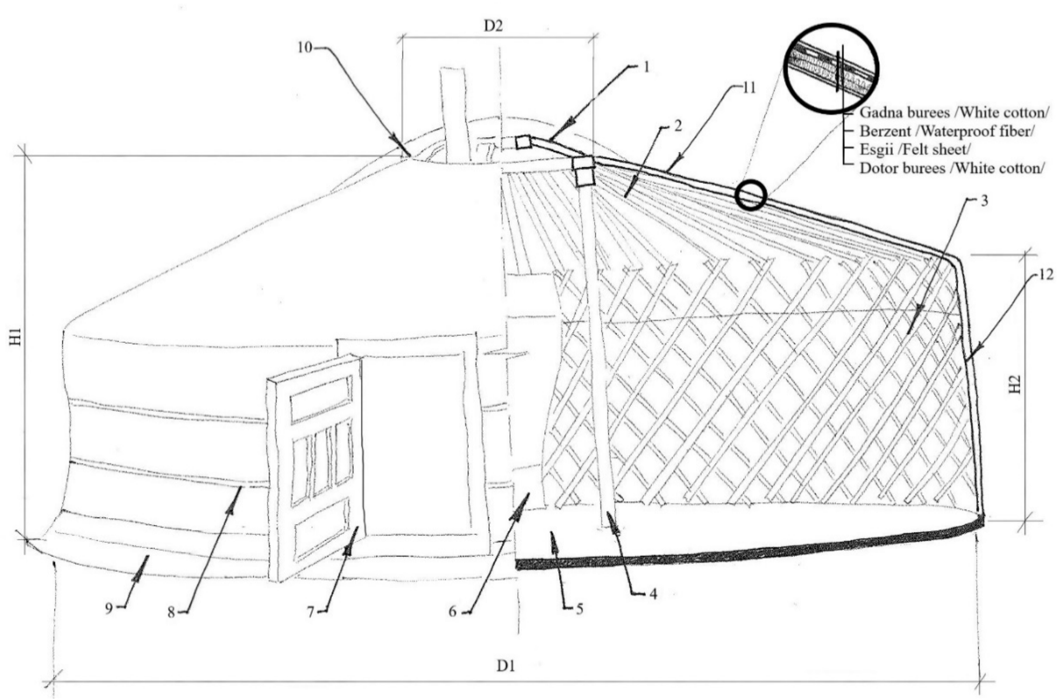
2.3.3 Structure and size of the *gers*

The appropriate design, material, structure, and size of each part of the *ger* have been specified by the Mongolian Agency for Standardization and Metrology (MASM) (2003, 2007). Based on the present survey, Fig. 2.11 illustrates the structural design of the surveyed *gers* with reference to specifications of the MASM (2003, 2007). The external and internal photographs of the *ger* are shown in Figs. 2.12 and 2.13, respectively.

Respondents reported that all *ger* construction procedures can be completed within several hours with the assistance of two to four adults. Some of the respondents described the typical construction process of the *gers* as follows. (1) The floor consists of seven interlocking flat wood plates, which are placed on the ground; (2) the *hana* (made of several latticed wood pieces) is unfolded and built into a circular wall; (3) a *khaalga* (door) is connected to the two ends of the *hana* using a rope. Usually, the *khaalga* faces south. Then, (4) two pillars are erected at the center of the *hana* to support the *toono* (skylight), and the *uni* (poles) are connected to the interior sides of the *hana*; (5) the exterior of the entire structure is covered with an *esgii* (layered felted wool insulation); finally, (6) a *busluur* (rope) is hooped around the *hana*, tightened, and secured. This procedure is similar to those reported by Alexander et al. (2006) and Maidar and Darisuren (1976).

The size of *gers* is classified by the number of lattice-shaped pieces named *hana* according to specifications of the MASM (2003, 2007), which are used to make the round wall of a *ger*. There are nine categories, namely, three, four, extended five, six, eight, ten, twelve, fifteen, and twenty *hana ger*. The distribution of the surveyed *ger* types is listed in Table 2.3 with the national statistics data (National Statistical Office of Mongolia, 2016). Four, five, six, and eight *hana ger*s are generally used as living spaces, and five *hana gers* are used by more than half of the total households.

Dimensions of the types of surveyed *gers* as well as those of the national standard (Mongolian Agency for Standardization and Metrology, 2003, 2007) are listed in Table 2.4. The floor area, room volume, and area of the *ger* envelope exposed to outdoor air, which were estimated based on the national standards, are also included as essential variables for calculating the heating load. The measured sizes were marginally different from the national standard because the components of a *ger* are fixed to each other by ropes.



Legend: (1) *toono* (skylight); (2) *uni* (pole); (3) *hana* (wall); (4) *bagana* (pillar); (5) *shal* (wood floor); (6) *hushig* (inner curtain for wall); (7) *haalga* (door); (8) *busluur* (hoop rope); (9) *hayaawch* (lower edge of *hana)*; (10) *urkh* (skylight cover); (11) *deever* (roof cover); (12) *tuuraga* (wall cover)

Fig. 2.11 Detailed structural illustration of a standard *ger* based on the observations of this study and specification of the national standard of Mongolia,
As illustrated by the authors with reference to the specifications of the Mongolian Agency for Standardization and Metrology (2003, 2007)
H1, H2, D1, and D2 correspond the dimensions listed in Table 2.3.

Fig. 2.12 Exterior of a *ger* in the 18th *khoroo*, Songino Khairkhan district, Ulaanbaatar

Fig. 2.13 Interior of a *ger* photographed during an interview conducted at the 18th *khoroo*, Sükhbaatar district, Ulaanbaatar

Source: Authors (photograph captured on August 19, 2018)

Table 2.3 Distribution of *ger* types based on the number of *hana* (wall units)

Type	Present Study	National Statistical Office of Mongolia, (2016)
Four	10%	17.4%
Five	84%	77.0%
Six	2%	2.3%
Eight	4%	3.3%

Table 2.4 Dimensions of surveyed *gers* classified by the number of *hana* with data of the Mongolian national standard (National Statistical Office of Mongolia, 2017)

***Ger* type**	**Mean and standard deviation of the size of each part. Values in parentheses indicate the national standard** (National Statistical Office of Mongolia, 2017)					**Floor area**	**Outer surface area**	**Interior volume**
	H_1	**H_2**	**D_1**	**D_2**	***n***			
Four *hana*	Mean 215 cm SD 13 cm (220 cm)	Mean 143 cm SD 3 cm (145 cm)	Mean 470 cm SD 7 cm (530 cm)	Mean 113 cm SD 2 cm (125 cm)	4	22.6 m^2	45.90 m^2	39.10 m^3
Five *hana*	Mean 243 cm SD 14 cm (235 cm)	Mean 148 cm SD 4 cm (145 cm)	Mean 541 cm SD 22 cm (620 cm)	Mean 133 cm SD 7.5 cm (140 cm)	36	30.9 m^2	59.85 m^2	55.00 m^3
Six *hana*	Mean 237 cm SD cm (250 cm)	Mean 157 cm SD 0 cm (145 cm)	Mean 596 cm SD 0 cm (660 cm)	Mean 137 cm SD 0 cm (150 cm)	1	34.2 m^2	70.00 m^2	64.93 m^3
Eight *hana*	Mean 265 cm SD 14 cm (255 cm)	Mean 148 cm SD 4 cm (145 cm)	Mean 633 cm SD 22 cm (680 cm)	Mean 165 cm SD 7.5 cm (160 cm)	2	36.3 m^2	71.00 m^2	70.00 m^3

H_1: height from the floor to the *urkh* (skylight cover), H_2: height of the wall, D_1: diameter of the floor, D_2: diameter of the *urkh*, *n*: number of surveyed *gers*

2.3.4 Composition of *ger* envelopes

To estimate the heating load of a building, the composition and materials of building envelopes are essential factors. A *ger* envelope consists of several layers of insulation, waterproofing, and artificial materials, and buyers have the flexibility of selecting a product for each layer at the market based on their preference and financial situation. Hence, the author interviewed the residents to determine their knowledge of the composition of a *ger* envelope and the role of each layer. Consequently, the author confirmed that all interviewees were knowledgeable about the type of materials used in their *ger* envelopes and had a common understanding of the function of each layer.

The answers provided by the occupants regarding the external cover used in the winter season are summarized in Table 2.5. The standard thickness of layers is as stipulated by the MASM (2007) is also included.

Table 2.5. Layers used in *ger* envelopes during the winter season

Layers	**Name**	**Explanations from interviewees**	**Ratio of usage in surveyed *gers***	**Standard thickness (MASM, 2003)**
Cotton	*Gadne tsagaan burees*	A thin white sheet used as the outermost cover for aesthetic purposes	100%	0.3 mm
Tarpaulin	*Berzent*	Water protection	65%	1.0 mm
Polyethelene		Optionally used for water protection	20%	
Paper insulation		Insulation	18%	
Felt sheeting	*Esgii*	Insulation	96%	15.0 mm
Polyethelene		Optionally used as a moisture barrier to avoid condensation	20%	
Cotton	*Dotor tsavag* and *Tuurga*	Thin white sheets, which are predominantly used as an innermost layer for roofing and walls	94%	0.3 mm
Carpet		Interior decoration and wall insulation	20%	
Synthetic carded wool	*Zulhai*	Insulation	6%	10.0 mm

*Each row is sorted in order from the outside to the inside based on the placement of the layers.

The outer side of surveyed *gers* was covered by a white fabric called *Gadna Tsagaan burees*. The *Gadna Tsagaan burees* is primarily used for an aesthetic purpose. The respondents explained that the white appearance of a *ger* has symbolic meaning in its long history. Most of the surveyed *gers* were using waterproof sheets called *berzent* beneath the outer white fabric. The purpose of this layer is to prevent water leakage and protect the residents from the cold wind in wintertime. As this waterproof layer degraded gradually, most households replaced it with a new one or replaced it with polyethylene sheets at a suitable timing. However, nine residents said that they had retained the degraded *berzent* in their *gers*, thinking that it would provide a small amount of heat insulation, and added a new *berzent* or polyethylene sheets beneath the *berzent*. Beneath the waterproof layer, felted wool sheets named *esgii* were used for insulation in 96% of the surveyed *gers*. The types of *esgii* are mostly brushed sheep wool (Mongolian Agency for Standards and Metrology, 2008). This felt sheet layer usually consists of two layers for adequate thermal insulation in cold winters. In contrast, carded polyester wool, which is known as *zulhai,* was used in 4% of the surveyed *gers* owing to its low price, although it is widely known for its lower insulation performance. Moreover, some households were using paper or polyethylene sheets in addition to felt sheet insulation, expecting an increase in insulation properties. A few respondents claimed that adding a polyethylene layer may cause condensation; thus, they switched the placement of the polyethylene layer from the outer side to the inner side of the *esgii* during winter. At the innermost layer, 94% of households used a white fabric called *dotor tsagaan tsavag*. The primary purpose of this layer is to protect the felt sheets from flaking off and falling into the interior space of the *ger*. Some households were using carpets on their interior walls.

The usage of felt sheets in the surveyed *gers* in summer and winter is listed in Table 2.6. Two layers of felt sheets are generally used for both seasons, and approximately 49% of the households changed the number of felt sheets depending on the season. Further, when the author visited *gers* in summer, most of the surveyed households had rolled up the hem of the wall layers to create openings near the floor for natural ventilation. Fig. 2.14 shows the rolled-up hem of the *ger* envelope.

From an architectural and engineering perspectives, buildings are assumed to be permanent and are constructed for long-term use. In contrast, the *ger* envelope is adaptable to the seasonal change of the weather, which is a similar to how people change their types of clothing to adapt to weather and climate. Nevertheless, it is noteworthy that approximately 25% of the households spent winter with just one layer of felt sheeting because of financial limitations.

Table 2.6. Breakdown of number of felt sheets (*esgii*) in sampled *gers* during the summer and winter seasons

Number of layers	During summer	During winter
One	45%	25%
Two	51%	62%
Three	4%	13%
Zero	0%	0%

Fig. 2.14 Photo of the roll-up hem of *ger* envelope

2.3.5 Compositions of floor materials

The floor materials in the surveyed *gers* are listed in Table 2.7 with the ratio of usage. Although the national standards (Mongolian Agency for Standardization and Metrology, 2003) specify wood as the floor material, more than half of the surveyed *gers* were built on bare ground with only a thin layer of linoleum, which was the most common covering because of financial limitations. Only one household had used laminate on a concrete slab. Half the floor in some *ger*s were covered using carpets or felt sheets. Households usually do not cover the entire round-shaped floor using carpets or felt sheets because of difficulties in cleaning the dust due to their usage of coal stoves. The interviewees reported that they need to frequently dump ash outside and bring coal inside for the stove in winter; consequently, the top layer of the floor must be replaced every year owing to degradation.

The current national standard does not specify floor insulation, which is probably because the MASM has focused on highly mobile nomadic *ger*s. In rural areas, nomadic households usually insulate their floors with dung, which is as easily accessible material. However, in urban areas, dung is not available and none of the surveyed participants used any particular insulation layer on the floor. Approximately 26% of the floors of the surveyed *ger* were covered with a few layers of cardboard, and just 6% of the floors were insulated using thin foam and foil sheeting.

In addition to the wall, roof, and floor, the national standard recommends the insulation of the joint between the lower edge of the walls *(hana)* and the floor with a felt sheet and tarpaulin. The surveyed respondents also used various measures to prevent a cold draft through the joint between the lower edge of the walls and floor. Table 2.8 lists the methods used to improve the airtightness of the joints between the wall and the floor. Approximately one-half of the households used old flour sacks. Fig. 2.15 shows the ground filling used outside at the joint between the wall and the floor of the *ger*.

As shown in Fig. 2.12 a temporary wind break room in front of the door was attached to 21 of the 49 *gers* to reduce heat loss and cold ingress through the door in winter. This windbreak room is usually made of single-layer plywood boards; the average size was approximately 1.7 m × 2.3 m of the floor size and approximately 1.8 m in height. A windbreak room was also used as extended interior space for the storage of coal, wood, and other supplies. Some of the households dismantled the windbreak rooms during the summer and set them apart from the *ger* to enhance natural ventilation.

Fig. 2.15 External view of the joint between the wall and the floor of a *ger*

Table 2.7 Materials used for the floor in surveyed *gers* during winter

Type of covering	Ratio of usage
Fully covered carpet	57%
Half-covered carpet	15%
Linoleum	89%
Laminate	2%
Wood floor	51%
Thin insulation pad	6%
Cardboard box	26%
Reflective insulation	6%
Dry livestock dung	4%
Concrete	19%
Condensed gravel	36%

Table 2.8. Methods used in surveyed *gers* for improving the airtightness of joints between the wall and the floor

Methods	Ratio of usage
Used floor sack	47%
Waterproof fabric	39%
Felted and waterproofed fabric	9%
Old clothing and waterproofed fabric	6%

2.3.6 Lifespan of *gers*

The durability of *gers* is not clearly specified in the national standards (MASM, 2003, 2007, 1991, 2012). However, the MASM (2008) advised that the performance and quality of felt sheets (*esgii*) must be tested every five years. Some of the respondents who were working in shops and manufacturing plants of *gers* also explained that felt sheets can maintain their original insulation ability for approximately five years. They also recommended replacing the waterproof layer every two years. Moreover, respondents said that the wooden structure of the *ger* could last a human lifetime depending on the maintenance conditions and usage style.

Fig. 2.16 shows the breakdown of the total period that the respondents had been living in the current *ger* and plot for all the households that were surveyed. It was observed that 41 and 39% of households have lived in a current *ger* and plot for more than 10 years, in particular. The reason why the usage period for a *ger* is marginally greater than that of a plot might be because certain households have been continuously using the same *ger* even when they moved to a different location.

A scatter plot between the usage period of the felt sheets (*esgii*) and years living in the current *ger* is shown in Fig. 2.17. The *gers* were originally temporary housing for nomadic purpose; therefore, it is remarkable that 43% of households have lived in their current *ger* for over 10 years.

Moreover, 8.2% of households that have been in the current *ger* for more than 10 years had replaced the felt sheets within the past five years, which follows the recommendation of the national standard. However, approximately 55% of households living in the current *ger* for more than five years had never changed the felt sheets. The respondents did not replace the felt sheets due to their financial limitations or because they determined the replacement of felt sheets to be unnecessary.

Kawagishi et al. (2018) reported that the Mongolian nomadic people move approximately four times a year for suitable environmental conditions depending on their livestock. Conversely, 67 and 24% of the surveyed urban *gers* were dismantled and assembled back at the same plot either twice or once a year, respectively, to dry the felt cover and improve the insulation. This indicates that although *gers* have become homes of permanent residents in urban areas, the original procedure of reassembling the components has been regularly practiced because of the need to dry the envelope material and the light structure. To improve the thermal performance of the *ger* this fact should be considered.

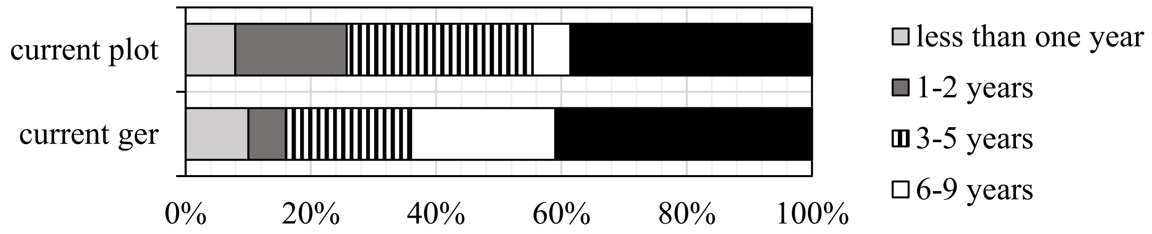


Fig. 2.16 Ratios of the period that each household has lived in their current *ger* and used the current plot

Fig. 2.17 Relationship between the replacement life of felt sheeting and number of years that the respondents have been living in the current *ger*

2.3.7 Manner in which current gers were obtained and factors influencing the purchase decision of *esgii*

Table 2.9 lists how households acquired their current *ger*. Half the households purchased a new *ger* at the market. Eight households inherited their *gers* from their parents and relatives and eight households purchased an old *ger* from friends, relatives, or based on newspaper advertisements. Five households acquired their *ger* from the donation of non-government or government organizations such as World Vision. Moreover, certain respondents received a *ger* or some insulation materials from politicians in an election year. Three households constructed the main wooden structure and other parts such as felted sheets by themselves.

Table 2.9 Manner in which households acquired their current *gers* (n = 49)

Method to own *ger*	**Number of households**
Inherited	8
Donation	5
Purchased old ***ger***	8
Purchased new ***ger*** from the market	25
Made by themselves	3

Owing to the well-standardized *ger* design, when people purchase a *ger*, they can freely choose the size of the *ger* and purchase separate parts according to their *ger* size from the various stores and manufacturers in the market. Therefore, the author surveyed the primary factors that influence the selection of felt sheets, which are the primary major materials that affect the insulation performance of the *ger* envelope. Table 2.10 lists the proportion of factors that influence the selection of felt sheets.

More than half the respondents were not knowledgeable about the factors that must be considered in the selection of felt sheets, and only 15 respondents explained the main factors that influenced their decision to select felt sheets. The cost of the felt sheet was the most influential factor, followed by physical characteristics, such as density, color, and odor. Moreover, the explanations provided by vendors were also considered. In the market, two colors of felt sheets were available, i.e., brown and white, and people generally assumed that the heavy and brown *esgii* was of higher quality. Moreover, diverse factors influenced the opinions of people regarding the physical characteristics of the felt sheets; for example, one person, who did not like the natural odor of the felt sheets said that “non-smelly” felt sheets have better quality, while another person said that “smelly” felt sheets are better because the odor of the felt sheets indicated that the wool had not been washed. They thought that unwashed wool preserves the natural lanoline, which results in stronger sheets that are beneficial for frequent stretching involved in the reassembling and dismantling processes.

Table 2.10. Factors influencing the decisions regarding felt sheeting purchases

(*n* = 49 households)

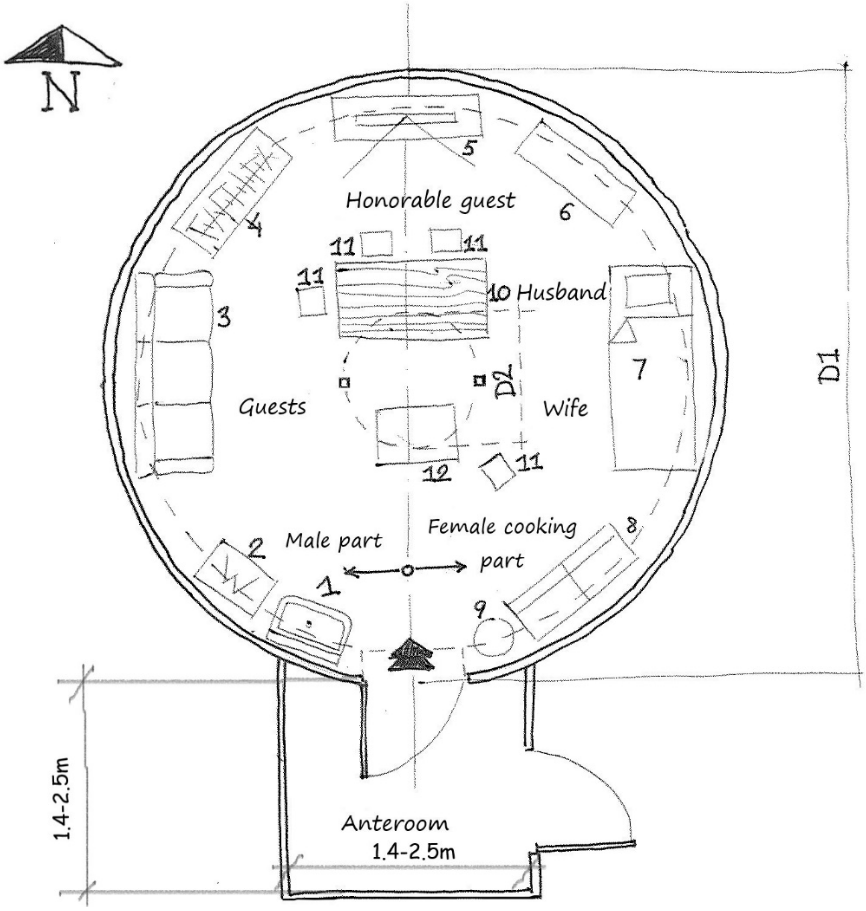
Factors	**Ratio**
Cost	20 %
Vendor advice	8%
Preference for pickled felt (*esgii*)	2%
Density	12%
Color	12%
Odor	4%
Thickness	2%
Manufactured in Mongolia	4%
No specific reason for selection	69 %

2.4. Results of the survey of urban *gers*: Interior space usage and space heating

2.4.1 Uses of the interior space.

The interior spaces of the surveyed *gers* were generally organized into several functional zones for activities without partitioning, which was also reported by Omoya (1997), Maidar and Darisuren (1976), and Alexander et al. (2006). Furniture arrangements determine the function of the area and the furniture arrangements in the surveyed *gers* was generally similar. Fig. 2.18 illustrates the typical floor plan of a *ger*.

Although the survey was conducted in summer when the daily mean outdoor temperature was approximately 17 °C, a coal stove was used for cooking in all the surveyed *gers*. A summary of interior functional arrangement in the surveyed *gers* is shown in Table 2.11. The right side of the entrance is used as the pantry, while the left side of the door was used for a sink and washing machine; the television was placed opposite the entrance. Beds and sofa were usually placed along the right or left side walls. In the center of the ger, a coal stove was installed. Most of the surveyed households placed their table near the stove, whereas a few of them placed it along the wall. The zone near the television, table, and chairs was assigned for meals and gatherings of a family and a study area, while the beds and sofa were used for sleeping and sitting.



Legend:

(1) Sink

(2) Washing machine

(3) Sofa or bed

(4) Closet

(5) Television set

(6) *Avdar* (wooden chest)

(7) Bed

(8) Pantry

(9) Cistern

(10) Table

(11) Chairs

(12) Stove

Dimensions D1 and D2 are listed in Table 2

Fig. 2.18 Common interior layout of the surveyed *gers*. Source: Authors

Table. 2.11 Summary of interior functional arrangement of households in a *ger* (n = 44)

	Pantry	TV	Bed	Table and chair	Washing machine and sink
South					
South-West					43
West		2	21	4	1
North-West		9	2	1	
North		20	11	1	
North-East		8	2		
East	1		22	11	
South-East	43			2	
Center				17	

Alexander et al. (2006) stated that a door is generally positioned to face the south side to avoid the cold north wind and introduce solar radiation to the interior space. In fact, the door of most of the surveyed *gers* was facing the south side; however, specifically, 95% of the doors in the surveyed *gers* were facing between the southeast and the southwest because of the geographical feature of the plots.

The usage of household appliances and furnishings of the surveyed *ger*s are listed in Table 2.12. For comparison, the data of a previous survey conducted in 2016 on 285,622 *ger*s (Bulgan. 2016) throughout the country—including nomadic *gers*—were also included as a reference. The most common appliances used in the *gers* were televisions, washing machines, refrigerators, and electric kettles.

Table 2.12. Ownership of appliances/furniture as observed in the sampled *gers* when compared to the data presented by Bulgan (2016**)**

Items	**Present study**	**Bulgan** (2016)
Appliances		
Television	100%	96%
Refrigerator	100%	59%
Washing machine	92%	67%
Electric kettle	84%	73%
Rice cooker	68%	59%
Electric hot pot	64%	68%
Electric stove	59%	15%
Freezer	30%	42%
Oven	22%	11%
Portable gas stove	20%	–
Vacuum cleaner	18%	30%
Computer	9%	–
Microwave oven	9%	–
Music player and speaker	4%	21%
Furniture		
Stool chair	100%	–
Cupboard	97%	–
Television stand	97%	–
Small table	81%	–
Bed	75%	–
Armchair	72%	–
Sofa	59%	–
Dresser	54%	–
Dining table	48%	–
Avdar (chest)	45%	–
Other		
Car	53%	–

In the previous survey, the proportion of users owing a refrigerator was smaller than that in the current survey. This is probably because nomadic *gers* usually are not connected to the main electricity supply and utilize energy from small portable solar panels. In contrast, the surveyed households used various appliances.

Notably, some electrical appliances used in *gers* are significantly more expensive than the price of a *ger*. As discussed in Section 2.6, a five-walled *ger* costs approximately MNT 2,200,000–2,500,000 (US$ 780-900), while the retail prices of LCD or plasma televisions, which are owned by 47 households, ranged from approximately MNT 330,000–16,000,000 at popular electronic stores in Ulaanbaatar in 2019. This price comparison underlines the affordability of *gers*. It is also noteworthy that approximately 53% of the households owned at least one car, which certainly costs more than a *ger*. However, it is a reasonable expenditure because most of the cars are used as taxis, which is an additional income source.

2.4.2 Types of space heating devices and the behavior of occupants related to stove usage

According to the explanation provided by the respondents, the heating period of their *gers* was from September to the beginning of June. Fig. 2.19 shows the ratio of households that required heating devices each month.

The heating devices used in the surveyed *gers* are shown in Fig. 2.20. Table 2.13 lists the proportion of heating devices used in the surveyed *gers*. Conventional and improved stoves were predominantly used for space heating, and 31% of households used stoves for cooking throughout the year. The improved stoves were used in approximately 59% of the surveyed households, and 4% of the surveyed households used an improved stove with an electric heating device for utilizing the subsidies for electricity usage in the nighttime. Nevertheless, an electric heater user said that the electric heating device was only used during nighttime as auxiliary heat source as the heating power of the electric heater was not sufficient for heating the entire *ger*.

As a part of the strategy of the Mongolian government to reduce severe air pollution with the support of the Asian Development Bank (ADB) and JICA, refined coal was sold in the market during the period 2017–2018. Further, since May 15, 2019, the Mongolian government and Ulaanbaatar city officials have prohibited the use of raw coal in six major districts in Ulaanbaatar and offered refined coal as an alternative source (*Air Pollution Reduction Department*, 2018). In a past survey conducted by the ADB and JICA (Asian Development Bank and Japan International Cooperation Agency, 2018), 63.8% of 120 surveyed households evaluated the refined coal as good or very good; however, the current survey determined that only 2 out of 49 households have used refined coal, and they were not satisfied with its heating performance, claiming that their consumption of refined coal is larger than that of raw coal.

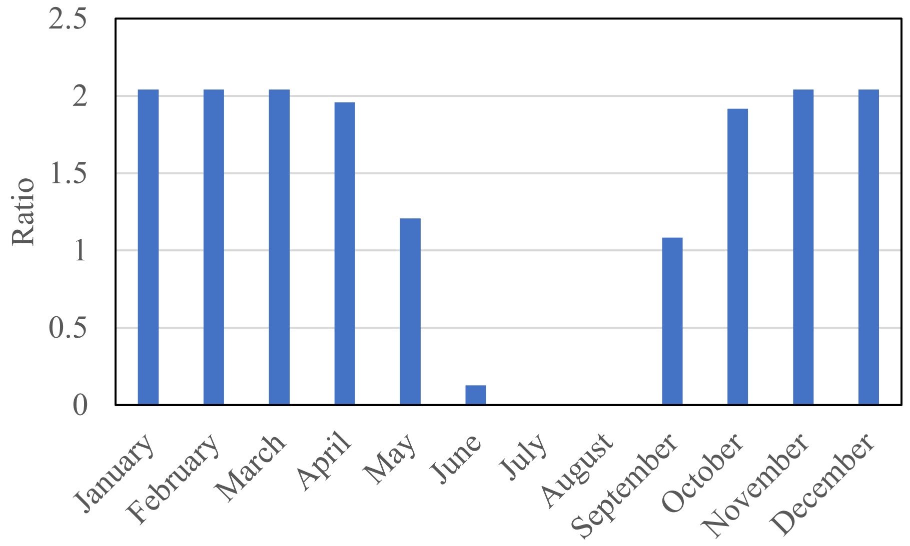


Fig. 2.19 Seasonal changes in the heating requirement

(a) Improved stove (b) Conventional stove (c) Electrical radiant heater

Fig. 2.20 Types of heating devices used in the surveyed *ger*s. Source: Authors (photograph captured in 2018)

Table 2.13. Breakdown of primary space heating measures in the sampled *ger*s ($n = 49$).

Items	Proportion
Improved coal stove	59%
Conventional coal stove	35%
Improved stove + Electric heater	4%
Wood stove	2%

2.4.3 Perception of the resident regarding the coal stoves

The perception of the residents toward improved coal stoves is listed in Table 2.14. In general, improved stoves are supposed to have a higher energy efficiency and lower emissions of air pollutants than conventional ones. The survey result suggests that most owners were satisfied with their improved stoves. Ten respondents explained the reason for their high satisfaction regarding the improved stove; first is the improved performance in terms of energy efficiency, and the second is the longer coal-burning duration, which reduced the frequency at which coal is added. However, 9% of respondents were not satisfied with the performance of the improved stoves because of the marginally complex procedure for ignition when compared to the conventional ones. In the case of the improved stoves, burnt embers and ashes have to be completely removed before every fire ignition, and a stove must be clean, which was considered as extra work by the occupants. Moreover, respondents stated that improved stoves usually exhibited problems when adjusting the burning process as it ages, which causes overheating or excessive ignition.

Table 2.14 Perception on improved stoves among representative members of each household in the survey (n = 34)

Answers	**Proportion**
Very satisfied	46%
Satisfied	31%
Slightly satisfied	14%
Slightly unsatisfied	3%
Unsatisfied	6%
Significantly unsatisfied	0%

The author also asked conventional stove users about their interest in the improved stove, as shown in Fig. 2.21. In this case, 68% of the respondents expressed an interest in improved stoves. Five respondents mentioned that conventional stoves were more likely to cause burn injuries, particularly in children, because a hot, wide iron plate is directly exposed to the room atmosphere. However, three respondents explained that they were using a conventional stove for cooking, but the improved stove could not be used for cooking in the case of large families; therefore, they preferred a conventional stove having a wider upper plate that is more suitable for placing a big pot. One respondent had used an improved stove in the previous year but replaced it with a conventional stove.

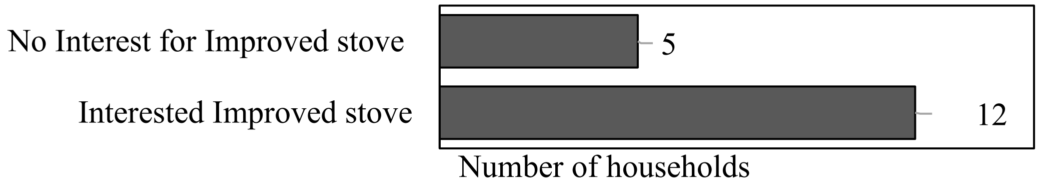


Fig. 2.21 Interest expressed by conventional stove users in the improved stove (*n* =17)

People usually built a fire three or four times a day, and after fire ignition, the coal continues to burn until the fuel is completely combusted. Approximately 17% of the surveyed households used their stoves all day when occupants stay in their *ger* all day. Fig. 2.22 shows the daily frequency at which coal is added in winter. The coal is generally added to a stove during the morning hours from 6 to 9 a.m. and at evening from 5 to 8 p.m. According to the respondents, a duration of 20–30 min is required to warm up the entire *ger* after the fire ignition, and respondents considered this duration is tolerable.

Unlike air conditioners, coal stoves exhibit limited functionality in terms of adjusting the combustion intensity to achieve a preferable room temperature. Fig. 2.23 shows the methods that are generally followed by the surveyed households to regulate the internal temperature. The residents usually adjust their indoor thermal condition by using a baffle of a chimney, opening the front of the stove, and adjusting the amount of fuel. Note that the improved stoves have a tunable baffle at the chimney to control the amount of outflow from a stove. The percentage of households that modulated the fire by the stove door and amount of fuel used were 14 and 20%, respectively. Furthermore, surprisingly, 18% of households sometimes opened the door or skylight (*toono*) and directly introduced cold outdoor air to avoid overheating. This suggests that the limited functionality of the coal stove in modulating the heating power results in a large amount of wasted fuel and pollutant emissions.

It is remarkable that, in 2018, stove-related residential fire accidents was 20.4% of the total fire accidents in Ulaanbaatar; moreover, 27.6% of stove-related fire accidents were due to fire leakage from the combustible equipment and blowing of ashes (National Department of Public Safety, 2018). Moreover, the usage of a coal stove requires frequent physical activities to bring the coal indoors from the usual storage locations outside the *ger*. The coal is sold by trucks (known as "porters") in small sacks in sizes of 10–30 kg. Approximately 60% of the surveyed households purchased coal and wood in sacks every three to five days from retailers and transported them to their homes via a car or carriage. The rest of the households purchased coal in tons with the truck, which is delivered to their home by vendors.

Although the current *gers* in the *ger* districts are considered temporary dwellings, many people live in *gers* for more than 10 years continuously. This fact suggests the importance of implementing a policy to improve the current living condition of *ger* residents. Specifically, replacing coal stoves with clean-energy heating devices should be considered to reduce pollutant emission to improve indoor air quality and the living quality in *ger* housing.

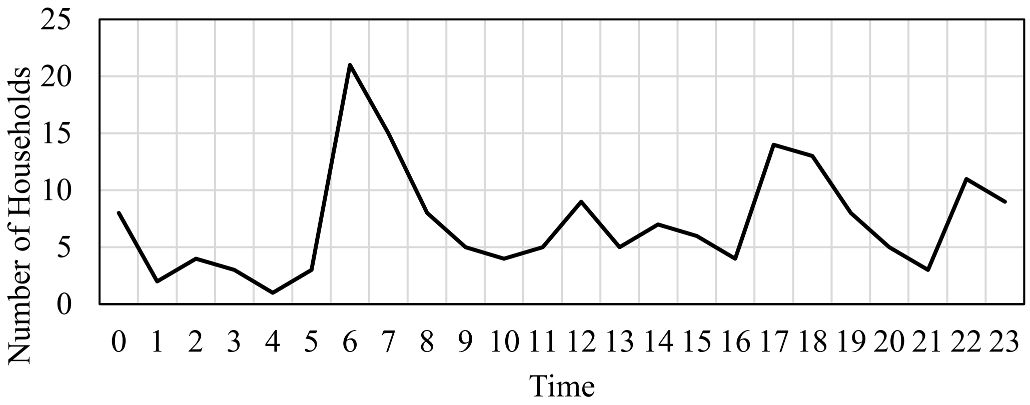


Fig. 2.22 Frequency at which coal is added in winter (n = 49)

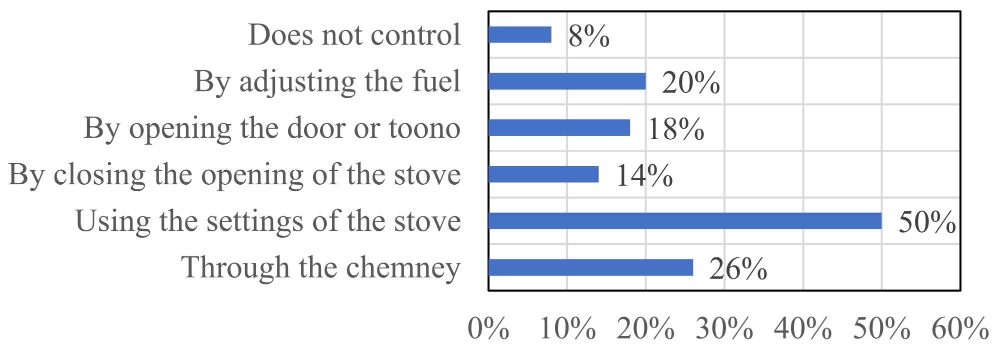


Fig. 2.23 Methods used by residents to adjust the indoor temperature (n = 49)

2.4.4 Fuel consumption in the surveyed *gers*

The respondents were asked about their annual coal and wood consumption. Households purchased coal and wood in different sizes; some of them were purchased in sacks while some of them were purchased in tons along with a small truck. Therefore, the author converted the different sizes of coal and wood into tons and cubic meters, respectively. Table 2.15 lists the average annual fuel consumption classified by the type of stoves. This result is similar to the previous survey of the ADB and JICA (2018).

Based on the fuel consumption data, the statistics of annual energy consumption of the surveyed *gers* was estimated as listed in Table 2.16. The data were estimated for not only the entire sample but also two groups categorized by the type of stoves, by assuming calorific values of 20 and 14.4 MJ/kg for coal and wood, respectively; moreover, the density of wood chips was assumed to be 600 kg/m^3.

Table 2.15 Average annual coal and wood consumption of the different stoves

Type of stove	**Coal [ton]**	**Wood [m^3]**
Conventional stove (n = 20)	Mean: 3 Standard deviation: 1.3	Mean: 3.3 Standard deviation: 2
Improved stove (n = 29)	Mean: 2.5 Standard deviation: 0.8	Mean: 2.5 Standard deviation: 2

The annual energy consumption per unit floor area of improved stove users is 18% lesser than that of conventional stove users. However, the standard deviations of both improved and conventional stove users are relatively large, indicating a diverse distribution of energy consumption. Factors that may cause differences in energy consumption were examined by evaluating the correlation coefficient with several building and behavioral conditions; however, there was no definite correlation between energy consumption and envelope surface area per indoor volume, heating hours, number of occupants, and thickness of *ger* envelopes. The potential reason why the energy consumption showed minimal correlation with these variables is because the currently used coal stoves have no accurate control to modulate the fire intensity to achieve the target indoor air temperature. Therefore, the stove combustion state depends on the fuel usage of the residents in each ignition. As previously mentioned, people adjusted the indoor air temperature by opening a door or skylight in case of overheating. This implies that the current coal stove usage will not have significant energy saving even if the insulation performance of the *ger* envelope is improved.

The heat loss coefficient of a *ger* was estimated based on the average annual fuel energy consumption per floor area and heating degree hours (HDH) obtained from the annual weather data of Ulaanbaatar in 2018 under the assumption of a minimum acceptable indoor air temperature of 18 °C (MASM, 2007). Table 2.17 shows a comparison with previous studies on energy consumption per floor area and heat loss coefficient. The estimated heat loss coefficient was 4.28 W/m^{2}K, which is approximately nine times higher than the required value of newly built houses in Hokkaido, Japan (Maruyama and Mori, 2019).

Table 2.16 Statistical summary of annual energy consumption of the surveyed *gers* using coal stoves for space heating

	Annual energy consumption [GJ/year]			**Annual energy consumption per floor area [GJ/m^2 year]**		
	Imp. stove	**Con. stove**	**Total**	**Imp. stove**	**Con. stove**	**Total**
Average	71.07	85.49	75.43	2.30	2.79	2.51
Median	65.28	94.56	65.28	2.11	2.33	2.22
Standard deviation	27.06	36.39	32.25	0.91	1.44	1.13
Maximum	141.12	154.56	154.56	4.57	5.48	5.48
Minimum	24.00	32.64	24.00	0.78	1.06	0.78
n	31	17	48	31	17	48

Imp. stove: Improved stove; Con. Stove: Conventional stove.

Table 2.17 Comparison with previous studies on energy consumption and heat loss coefficient

	This study	**Buyantogtokh and Zhang (2019)**	**Ishikawa *et al.* (2007)**
Heat loss coefficients	4.28 W/m^{2}K	1.31 - 3.96 W/m^{2}K	17.2 W/m^{2}K
Energy consumption per floor area	2.5 GJ/m^2	NA	3.05 GJ/m^2

2.4.5 Winter clothing worn by residents of *gers*

Clothing worn by the residents can have a substantial effect on thermal comfort. Therefore, the indoor clothing of residents in winter was surveyed, and the author estimated the total amount of thermal insulation of the winter clothing as clo values based on the specifications of the ASHRAE Standard 55 (2010). Clo is a unit to express the thermal insulation of clothes worn by people.

The relationship between the clo values and the age of residents is shown in Fig. 2.24. It should be considered that the clo values of standard western business attire of a suit and tie are approximately 1.0, which is equivalent to 0.155 Km^2/W. In contrast, the clo values of surveyed households varied between 0.2 and 1.83 clo. Clothing insulation of female elder occupants was generally higher than those of others, while residents younger than 20 years old showed marginally higher values than middle-aged people. When considering the clothing insulation by gender, the median clo values of all respondents for males and females were 0.64 (n = 23) and 0.55 (n = 47), respectively, which are similar to the values in office buildings located in California, Michigan in the US, Canada, and Australia during winter, where the median clo values of female and male employees were 0.67 (n = 2786) and 0.63 (n = 3547), respectively (Schiavon and Lee, 2013). Clothing insulation of the residents of the surveyed *gers* was surprisingly low despite the low thermal performance of *ger* envelopes as well as the necessity to frequently go outside for using the toilet. The large amount of energy consumption described in Section 2.4.4 is consistent with lifestyles of the Mongolian people.

Fig. 2.24 Relation between clothing insulation and the age of the occupants

(Female n = 47; Male n = 23)

2.4.6 Perception of the residents regarding indoor thermal comfort in winter

The thermal perception of occupants living in a *ger* in winter in terms of indoor temperature and thermal satisfaction was surveyed partially based on the specifications of the ASHRAE Standard 55 (2010).

The responses to the question, "How do you rate the internal temperature of your *ger* during the winter season?" are listed in Table 2.18. All respondents chose "either too cold or too hot," suggesting significant fluctuations in indoor air temperature. According to the explanations provided by the respondents, the indoor temperature quickly drops when they open a door or the coal in the stove is depleted. However, none of the interviewees stated that they felt "often too cold," but approximately 76% stated "often or occasionally felt too hot." Taken together, these responses imply that coal stoves with excessively high heating power for small *ger*s are being used to compensate for the low thermal performance of the *ger* envelopes.

The responses to the question, "How do you evaluate the overall thermal comfort level of the internal environment in your *ger* during the winter season?" are listed in Table 2.19. This question was used to evaluate the overall thermal comfort satisfaction. Approximately 85 % of the interviewees evaluated over all indoor thermal as comfortable in contrast, no one evaluated the temperature as neutral (no temperature discomfort), as listed in Table 2.18. This suggests that overheating by a powerful stove might be perceived as good under extremely cold outdoor conditions.

Table 2.18 Distribution of responses to the question: "How do you rate the internal temperature of your *ger* during the winter season?" (n = 67)

Response	**Proportion**
Often too hot	6%
Occasionally too hot	16%
Occasionally too hot and too cold	54%
Neutral	0%
Occasionally too cold	9%
Often too cold	15%

Table 2.19 Distribution of responses to the question: “How do you evaluate the overall thermal comfort level of the internal environment in your *ger* during the winter season?” (n = 67)

Response	Proportion
Very comfortable	15%
Comfortable	59%
Slightly comfortable	11%
Slightly uncomfortable	8%
Uncomfortable	7%
Very uncomfortable	0%

2.4.7 Motivation of the residents to improve quality of life

The motivation of the residents to improve their current living conditions was surveyed by the question, “Do you plan to improve your living conditions?” The distribution of responses is shown in Table 2.20, suggesting that the residents have a desire to live in a more comfortable environment. Approximately 8% of the respondents were planning to move into an apartment with basic infrastructure, while 4% of the respondents were interested in buying a larger *ger*. A greater number of respondents wanted to move to a *baishin* than an apartment, which is probably because of the cheaper cost of *baishins* when compared to apartments with basic infrastructure.

The minimum apartment price in the urban fringe area of Ulaanbaatar is approximately MNT 41,000,000 according to Smith et al. (2014). The minimum condition for receiving an apartment loan is an average monthly income above MNT 950,000 with 30% down payment. Only 16 % of the surveyed households satisfy this income requirement. In fact, the average monthly income of the surveyed households was approximately MNT 600,000. Therefore, relocation from a *ger* to an apartment is difficult for families living in a *ger*. According to the National Statical Office of Mongolia (2016), approximately 114,000 families lived in the *ger* districts of Ulaanbaatar, and coal stoves used in their *gers* are the current major source of outdoor air pollution during the frigid winter months.

Table 2.20 Distribution of responses to the question: "If you have any plans to improve your living conditions, what type of plan do you have?" (asked without a prompt)

Response	**Proportion**
Move to an apartment	8%
Move to a *baishin*	12%
Move to a larger *ger*	4%
Replace a conventional stove with improved stove	12%
Buy an electrical heating device	2%
Replace a heating device and improve the insulation performance of the *ger*	8%
Improve the insulation performance of the *ger*	19%
Desires improvement, but it is financially impossible	12%
Desires improvements, but lacks a plan	8%
Does not think that improvements are necessary	15%

2.5 Results of the market survey

The selling prices of *gers* in the Naran Tüul Market was investigated in August 2018. In the market, complete, ready-to-build *ger* kits and all types of replacement parts and tools, including uncut felt sheets are available for purchase. Usually small and medium-sized *gers* were ready for purchase at the site; however, larger *gers* were usually preordered.

According to this observation, although there was a large variety of options for buying *ger* products, significant price cuts were limited to large purchases, and there was no significant difference in the prices between stores. The typical prices of complete *ger* sets and the supporting material as observed are listed in Table 2.21.

In the market, the price of the most popular size of five-walled *gers* ranged from approximately MNT 2,200,000 to 2,500,000 while the price of one-layer felt sheets (*esgii*) for a five-walled *ger* was approximately MNT 720,000, which is around 28% of the total price of the ger. Further, a one-layer felt sheet for a four-walled *ger* cost approximately MNT 520,000, and the price of labor cost to prepare a felt sheet is approximately MNT 11,000–12,000 per square meter including cutting and sewing, which is equivalent to approximately US$4, based on the currency conversion rate in 2019.

Remarkably, a *ger* is a low-cost dwelling that becomes a home for rural-to-urban settlers. Based on our surveyed data, the median monthly income is MNT 600,000, as shown in Fig. 2.7, which implies that people can buy a relatively comfortable dwelling with three to four months of income. Although *ger*s are temporary and mobile tents that require frequent maintenance, the price of the ger is relatively affordable, which is probably due to its well-standardized design and materials that rely on domestic products, such as sheep wool.

For a comparison, Table 2.22 lists the average price of a 45 m^2 *baishin* and an apartment in Ulaanbaatar. The average price of an apartment per unit floor area as reported by the National Statistics Office of Mongolia (2016) is MNT 2,250,000/m^2, which suggests an average apartment of 45 m^2 costs approximately MNT 101.25 million. Thus, the cost of an apartment is approximately 14 times the annual income of the surveyed households. Hence, apartments are difficult to afford for *ger* residents.

Table 2.21 Market price of a *ger* and its relevant parts

Size of the *ger*		**Price [in MNT]**
Five-walled *ger*	Complete set of a *ger* with single-lined felt sheet	1,500,000
	Complete set of a *ger* with a double set of felt sheets	2,200,000–2,500,000
	Complete set of *ger* with a double set of felt sheets and carved ornaments	3,000,000
	Only wooden structure	900,000–1,300,000
	Single felt sheet	720,000
	Roof of stitched carded wool	280,000
	Waterproof fiber	270,000–360,000
Four-walled *ger*	Complete set of a *ger* with single-lined felt sheet	1,500,000
	Only wooden structure	800,000
	Single-lined felt sheet	520,000
Other separate material	Single-lined felt sheet for six-walled *ger*	1,000,000
	Imported felt:1 m (width 1.8 m)	12,000–15,000
	Machine made felt: 1 m (width 1.8 m)	90,000
	Pricked felt (with a needle): 1 m (width 1.8 m)	50,000
	Roof skylight cover (*urkh*)	20,000–50,000
	Encircling rope:100 m	70,000

Table 2.22 Average price of other types of dwelling units in Ulaanbaatar

Accommodation type	The average price in MNT	References
45 sq. m *baishin* with 0.07 ha plot	20,000,000	(NSOM, 2017)
45 sq. m apartment per sq. m	101,250,000	(NSOM, 2019)

2.6 Discussion

To reduce outdoor air pollution and improve indoor air quality, the officials of the Ulaanbaatar City Hall and the Mongolian government implemented a pilot project to boost nighttime electricity consumption for heating purposes in *ger* districts (Ulaanbaatar Electricity Distribution Network) in January 2017. During the heating season, from October to April, up to 700 kWh/month of electricity is provided free of charge to residents of the *ger* districts for use from 10:00 p.m. until 6:00 a.m.; moreover, when the electricity consumption exceeds 700 kWh/month, the remaining consumption is subsidized by 50%.

Considering the fact that the heating capacity of popular improved stoves is approximately 6.5 kW (Ulaanbaatar Services Improvement Project, 2015), a *ger* household using an improved stove for 12 hours per day would consume approximately 2.34 MWh per month, which costs approximately MNT 304,700 per month when electrical heating devices with an energy efficiency of 1.0 are used and the current subsidy is applied. In contrast, the average annual cost of solid fuel in mid-2019 was MNT 741,412, according to a survey by Ulaanbaatar statistics (2019), which clearly suggests the economic advantage of coal stoves in terms of running costs.

In fact, all survey participants stated that if electricity cost is as affordable as coal, they would prefer to use an electrical heating system instead of a coal stove. Conversely, five households explained the reason that they had not applied for this electrical subsidy scheme was because they do not have individual meters, while other households explained that they do not have an electrical heater.

Moreover, when we consider a policy for the replacement of coal stoves with electric heating systems for the entire *ger* district in addition to the households with financial resources, it was note that the power supply was insufficient for heating all the households in the *ger* district. The current power plants in Ulaanbaatar generate 0.9 GW of electricity (Ministry of Energy). When considering all the *ger* districts, there are 216,000 families living in *baishins* and *gers* that use electric heaters; therefore, the required power to heat all these households would be 1.2 GW, which is 30% higher than current electricity generation (Ministry of Energy).

Thus, we can infer that the policies that encourage a switch from coal stoves to electric heating devices require an additional policy that reduces the thermal load of the current *ger* districts. Chun-Kuen Tong, Jason and Phillip (2018) studied heat loss and air leakage of a *baishin* and indicated that it has low thermal insulating performance and suffers from significant heat loss; they also highlighted that the retrofitting of *baishins* can significantly reduce carbon emission. Following this research, an insulation subsidy project for *baishins* was implemented by the Mongolian government and the World Bank (Ulaanbaatar Services Improvement Project, 2018). However, there is no available support from the government to improve the thermal performance of *gers* in the *ger* district. When considering the support required by the large proportion of households that live in *gers* to switch from coal stoves to electric heaters, it should be noted that additional support is also required for the *gers* to improve the thermal performance of the *ger* envelope.

To improve the thermal performance of *gers*, a new method should be developed that considers the subsequently described specific features of the *ger*. First, although urban *gers* are not frequently moved, occupants still dismantle and rebuild *gers* at least once in a year because of the material and structure of the *ger*. Improvement to the *ger* insulation envelope should not interrupt this behavior and these improvements should have should have sufficient strength to withstand the tensile stresses during assembly. Second, all materials and components of the *gers* are currently well standardized and are readily available to the public in markets. Therefore, a new prototype should be standardized to the products that are available in the market. Third, people are used to the relative comfort and low price of the *ger*; therefore, people are expected to have a willingness to pay for insulation improvements that are not higher than the price of the *gers*.

2.7 Conclusion

More than half of the households in the *ger* district live in *gers* and their contribution to air pollution is substantial. Therefore, a countermeasure against the usage of coal stoves should not be limited to only *baishins,* and new actions targeting *gers* are urgently required. Nevertheless, there is a lack of policy implementation to improve the thermal performance of the *ger* envelope. To comprehend the current living conditions, behavior of the residents of *gers*, their perception toward thermal environment, materials used, and structure of the *ger*, a field survey was conducted on 49 urban *gers* in the *ger* district of Ulaanbaatar in August 2018.

The survey results indicate that the *ger* is an affordable dwelling for low-income households owing to its well-standardized design and local material. Although *gers* are inexpensive, it provides a relatively comfortable living environment and has become a home for migrants moving from rural to urban areas. However, as the residents are already used to such a low-cost and comfortable environment, they exhibit reduced willingness to improve the thermal performance of the *ger* envelope or replace coal stoves with energy-efficient clean heating devices.

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Chapter 3
Development of a Retrofitting Method for Improved Insulation in Urban *Gers*

3.1 Introduction

Nowadays, household coal stoves have become a major source of severe air pollution in Ulaanbaatar, Mongolia. Currently, 58% of the households in Ulaanbaatar rely on coal stoves for space heating and cooking (National Statistical Office of Mongolia, 2016b). This high fraction is primarily due to *gers* and detached houses located in *ger* districts, which are unplanned residential districts. To reduce emissions from coal stoves, the Mongolian government and World Bank replaced more than 40,000 conventional stoves used in *gers* into fuel-efficient stoves called *improved stoves* by introducing a subsidy ranging from 50 to 90% between 2011 and 2015 (Ulaanbaatar Services Improvement Project, 2015). Moreover, according to a JICA report, the major cause of fires in Ulaanbaatar is stove-related activities in the *ger* districts (*JICA Report,* 2012). With this background, to reduce stove usage, the government has implemented an insulation subsidy program for households living in *baishins* in Ulaanbaatar with the support of the World Bank and ADB (Ulaanbaatar Services Improvement Project, 2018; Building Energy Efficiency Center, 2018). However, this insulation subsidy has not been applied to households living in *gers*. It might be partly owing to its portable design, which causes difficulties to apply the usual insulation-related retrofitting methods that are applied to buildings. In 2015, 30.4% of the households in Ulaanbaatar lived in *gers* (National Statistical Office of Mongolia, 2016b); therefore, emission reduction from the usage of coal stoves in urban *gers* is a critical issue. To promote the relocation from urban *gers* to apartments with suitable infrastructures including heating, the Mongolian government sponsored a low-interest apartment project for low-income households (Boldbaatar, Takami and Fukui, 2017). However, the large-scale implementation of this project is highly challenging in the short term due to the economic situation of the country. In fact, Mongolia with a per capita gross domestic product of 4000 USD is currently categorized as a low and middle-income country (World Data Atlas, 2020).

A possible strategy to reduce outdoor and indoor air pollution would be replacing coal stoves with electric heaters. For example, Pillarisetti et al. (2019) conducted long-term observation of the performance of electric-driven air-to-air heat pumps tailored to the cold climate in *gers* and *baishins* and confirmed the acceptable performance of heat pumps. However, the shift from coal stoves to electric heating devices in urban *gers* with poor insulation will drastically increase the electricity demand in Ulaanbaatar, causing a need for investment in power supply facilities. Note that Mongolia imported 18.8% of electricity as of 2018. Moreover, the electricity connections in current households is insufficient to supply a large amount of electricity (Jamsran, 2018). Therefore, an additional policy to reduce the thermal load of urban *ger* houses is required.

Considering these circumstances, in this chapter, the author presents a newly developed retrofitting method of *gers* to reduce the heating load and electricity consumption under the scenario that coal stoves are replaced with electric heaters. To determine affordable methods tailored to the local conditions, the required factors for effective insulation methods are first discussed based on the field survey and observations that are described in Chapter 2. With these findings, the design of the newly developed method is presented.

3.2 Baseline conditions of urban *gers*

This section provides a brief summary of the features of urban *gers* based on the field surveys described in Chapter 2 and identifies the requirements for affordable measures to improve the thermal performance of *gers*.

3.2.1 Standard design and materials

The MASM (2003) stipulates the size and design of *gers*. Specifically, the size of a *ger* is differentiated by the number of lattice-wall units. There are *gers* with 3–8 wall units, with floor areas ranging from 22 to 36 m^2. In *ger* districts, 71% of the household live in five-walled *gers* (~30.9 m^2) (National Statistical Office of Mongolia, 2016b).

Fig. 3.1 shows one of the surveyed five-walled *gers*. A *ger* is a single round-shaped dwelling made of a wooden structure covered with sheets of wool felt. The felt sheet layers are covered with tarpaulin and a white fabric; tarpaulin is used for keeping the felt sheet dry and the white fabric is used for aesthetic purposes. The inner surface of the felt layers is usually covered with white cotton to prevent the felt sheets from flaking off and falling inside a *ger*. A wooden door is sometimes insulated with a self-made felt sheet layer, which is covered by waterproof tarpaulin as shown in Fig. 3.1(a).

Gers have no space for toilets; thus, people use outdoor toilets located on the same plot. Such a practice causes the indoor temperatures to drop whenever the door is opened in winter. To prevent the cold air from coming through the door directly and to extend the indoor floor area, 42% of surveyed *gers* were equipped with a simple self-built windbreak room that is attached to the entrance door, as shown in Fig. 3.1 (c).

Because of the highly standardized design, the diverse elements of *gers* are available in various shops. Thus, in most cases, people first select the size desired for a *ger* from multiple options, and then purchase *ger* elements from different stores and manufactures according to their preferences and financial situation or inherit used parts from acquaintances. Therefore, methods to improve the insulation of *ger* envelopes should be compatible with the standardized designs and also follow the current trends when using manufactured products, which should also be readily available in the market. Furthermore, standardization of windbreak rooms that can be assembled and dismantled would effectively assist in reducing the ventilation heating loss caused by the opening of doors.

(a) Exterior of a *ger* located at 18th *khoroo*, Sükhbaatar district, Ulaanbaatar (August 2018)

(b) Interior of a *ger* located at 18th *khoroo* Sükhbaatar district, Ulaanbaatar (August 2018)

(c) Windbreak room built by residents in the 8th *khoroo*, Bayangol district, Ulaanbaatar (August 2018)

Fig. 3.1 Photographs of a five-walled *ger* observed in the field survey

3.2.2 Construction and dismantling processes

To confirm the processes involved in the construction of a *ger*, the author obtained a set of all elements of a five-walled *ger*, and assembled it at Chikushi Campus, Kyushu University, Japan. The assembly process starts by untangling and affixing multiple lattice-wall elements by ropes to form a circular wall. Then, two pillars are set up at the center of the space to support the circular frame of a skylight. The lattice-wall elements and circular frame of the skylight are linked by poles. Fig. 3.2 shows the assembly process of the wooden structure. Finally, felt sheets and waterproof fabrics are placed over the wooden framework, tensioned well from the periphery to adjust their position, and then tightened firmly from the outside using ropes. Figs. 3.3 and 3.4 illustrate the covering process of a *ger* using a felt sheet. Fig. 3.5 shows the assembled *ger*. Dismantling involves the same process, but performed in reverse.

It is remarkable that 24 and 67% of the surveyed households dismantled and rebuilt their *gers* on the same plot once or twice a year, respectively, to dry the felt sheets and improve the insulation. This indicates that insulation-related retrofitting methods for *gers* should not distract from the regular practice of dismantling and assembly. The retrofitting process for improved insulation should also be easy so that it can be handled by the residents themselves.

Fig. 3.2 Assembly process of the wood structure of a *ger*


Fig. 3.3 Assembled wooden structure covered by a felt sheet


Fig. 3.4 Covering process using a felt sheet

a) Interior of the assembled *ger*

b) Exterior of the assembled *ger*

Fig. 3.5 Assembled *ger* in Chikushi Campus of Kyushu University

3.2.3 Financial requirement

As mentioned in Section 2.6, the average price of a five-walled *ger* in the Narantuul market in Ulaanbaatar ranged from MNT 2,200,000 to 2,500,000 (approximately US$ 770–880) as of 2019. Meanwhile, the average cost of an apartment with a similar floor area as a five-walled *ger* is approximately MNT 69,750,000, which is 27 times greater than the *ger* price in 2018.

Considering that the median monthly household income of families who reside in urban *gers* is approximately MNT 600,000, it is obvious that the financial situation has a significant influence on the decisions of residents to improve their *gers* for better thermal insulation and replace heating devices with low-emission ones. In fact, despite the recommendations of the MASM that users maintain the quality of felt sheets and replace them every five years (Mongolian Agency for Standardization and Meteorology, 2007), the felted sheets of most of the surveyed *gers* had not been replaced for more than five years, not only because of a lack of knowledge but also because of insufficient funds. Moreover, 67% of respondents chose felt sheets due to the lowest price. According to a national survey conducted with 1000 *ger* residents (The World Bank, 2009), the primary reasons why they do not replace a coal stove with electric heaters are the high cost and poor electrical connection of their home.

3.3 Developed system

3.3.1 Insulation panels

As a *ger* is made of a wooden frame covered with several sheets of wool felt, the first idea to improve the thermal insulation of the *ger* envelope was to add sheet-type thermal insulation materials such as glass wool. However, the insulation of a *ger* should be durable to the strong tensile forces when a *ger* is dismantled or reassembled. Therefore, sheet-type insulation materials used for contemporary buildings are inappropriate.

From this perspective, the author developed a prototype for the insulation-related retrofitting method for the *ger* envelope, which included the wall parts, roof parts, and the skylight.

Fig. 3.6 shows the developed insulation prototype for wall and roof parts. To create a circular-shaped wall, the insulation layer was divided into 20 rectangular panels of equal sizes. Further, the insulation layer covering the conical roof consists of two types of panels divided into 20 circumferential sections. The panels are composed of insulation board-based core, which is covered with a white fabric. These panels are connected by Velcro to reduce air leakage through the gaps between the panels. The wall insulation panels can be attached to a wooden lattice-wall structure by ropes. The roof insulation panels are also attached to the roof poles using ropes.

Fig. 3.7 shows the details of the insulation panels for a five-wall *ger*. Figs. 3.8 and 3.9 show the details of roof and wall insulation panels, respectively. Fig. 3.10 shows the insulation panel for a skylight, which is also attached to the wooden frame by ropes. It has an opening for the chimney of a coal stove.

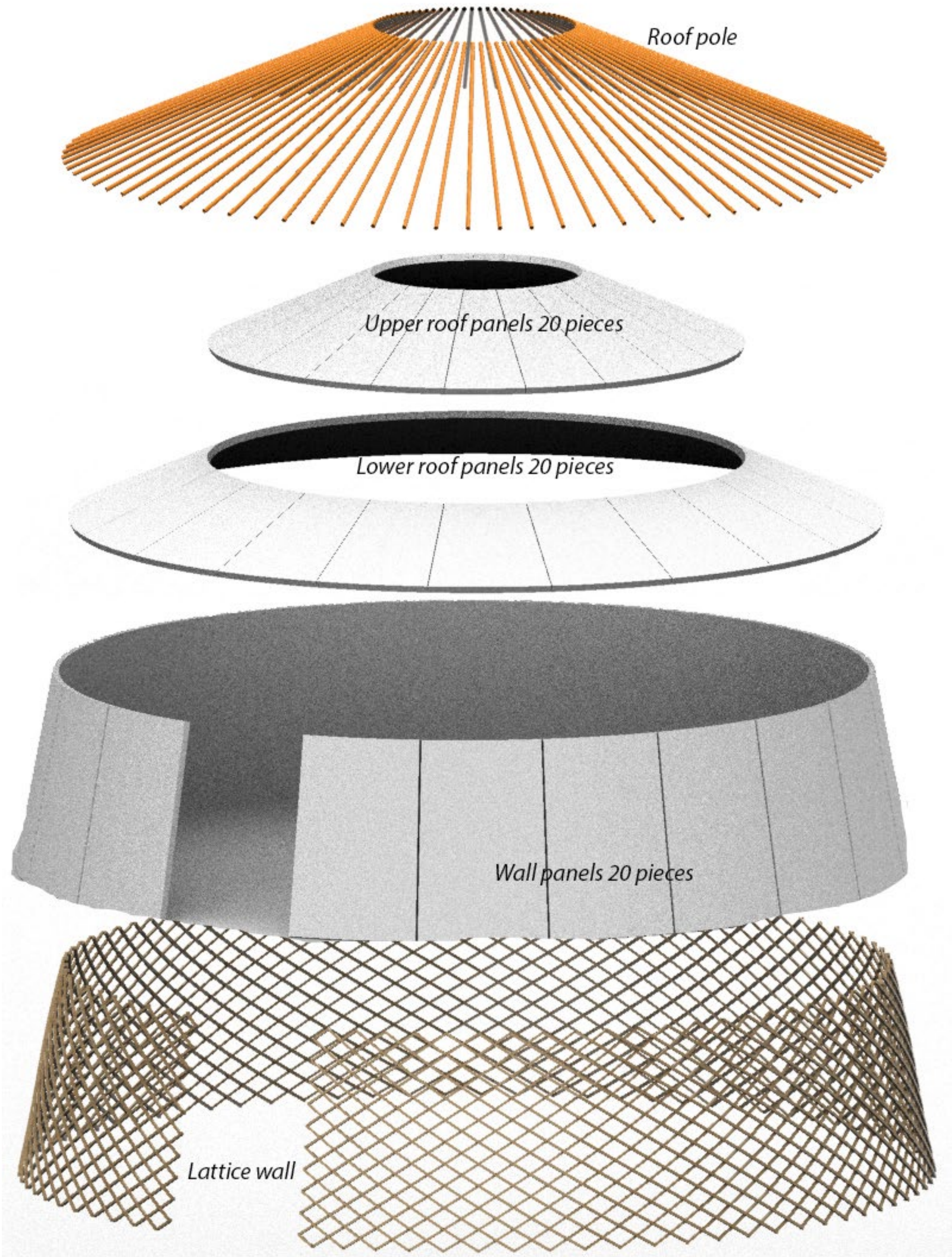


Fig. 3.6 General installation concept for insulation-related retrofitting

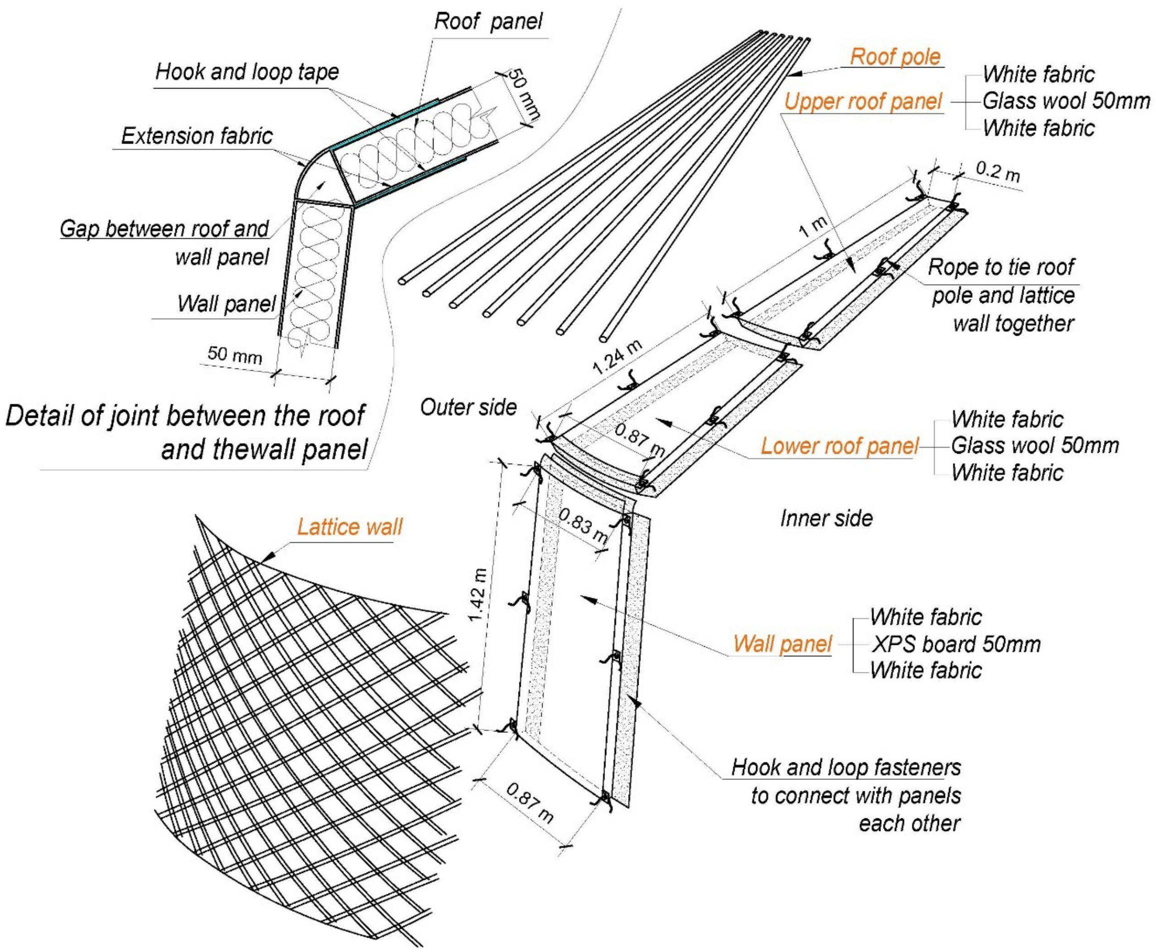


Fig. 3.7 Details of the installation of the retrofitting

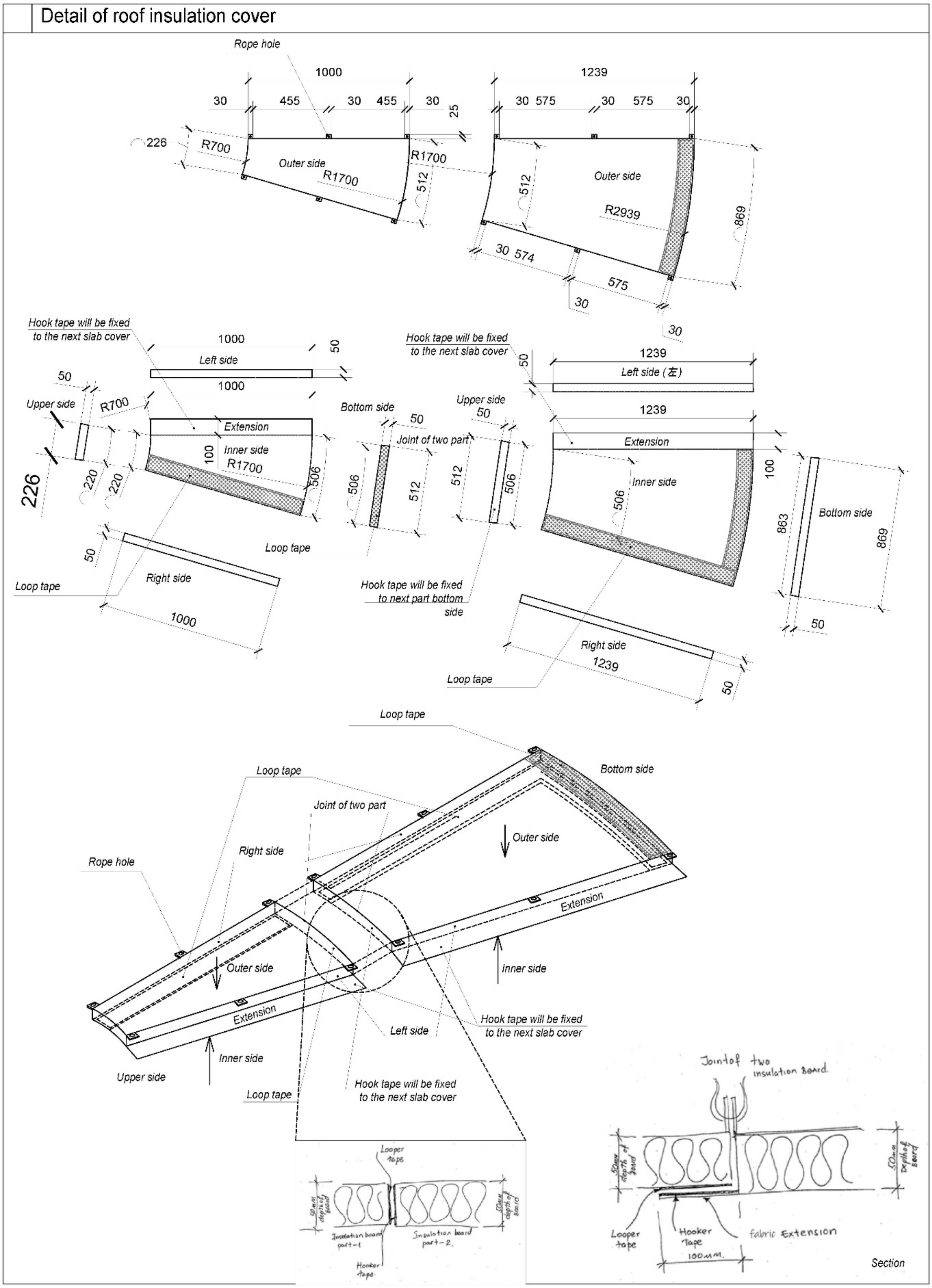


Fig. 3.8 Details of the roof panel cover (dimensions are in millimeters)

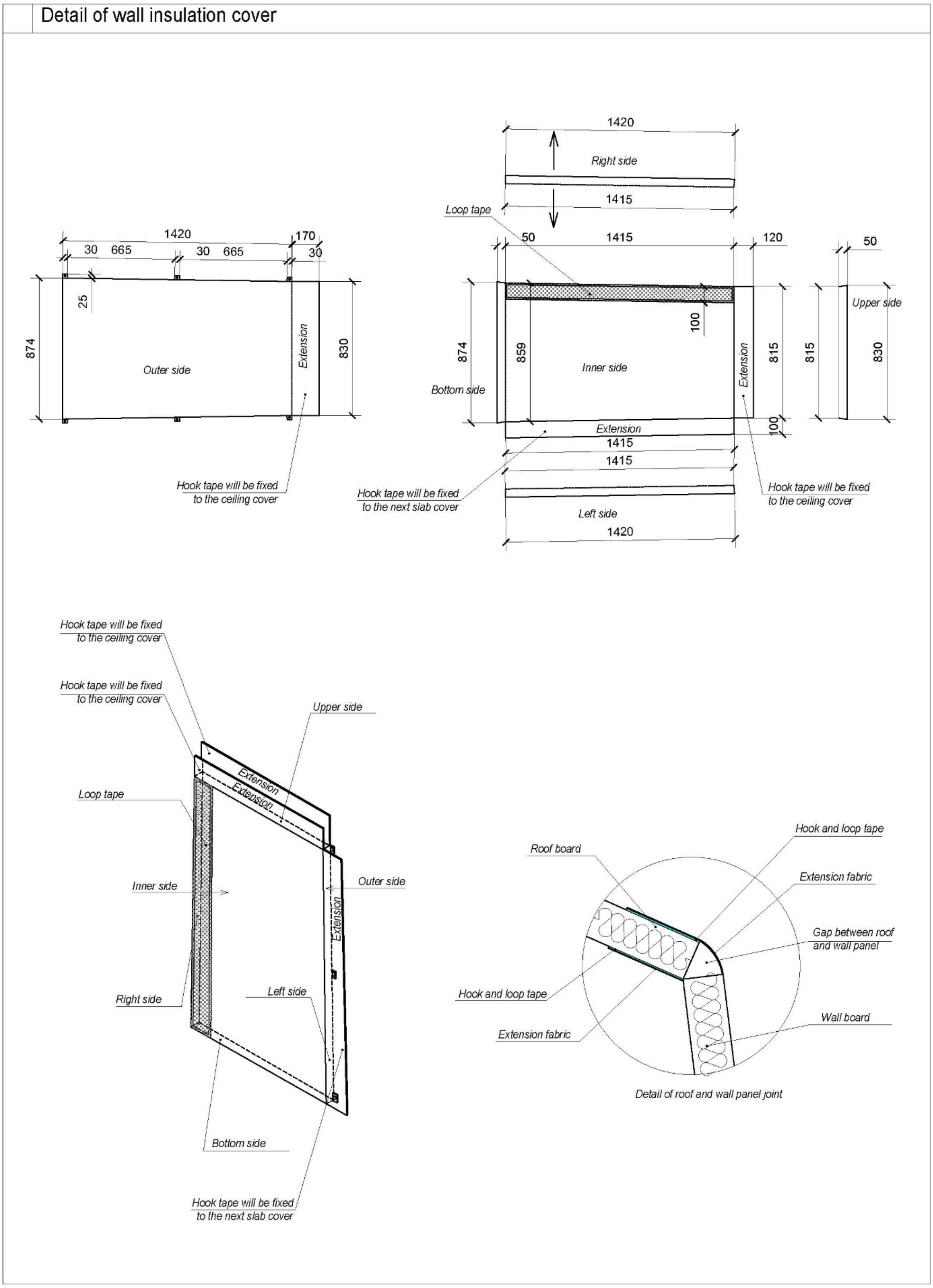


Fig. 3.9 Details of the wall panel cover

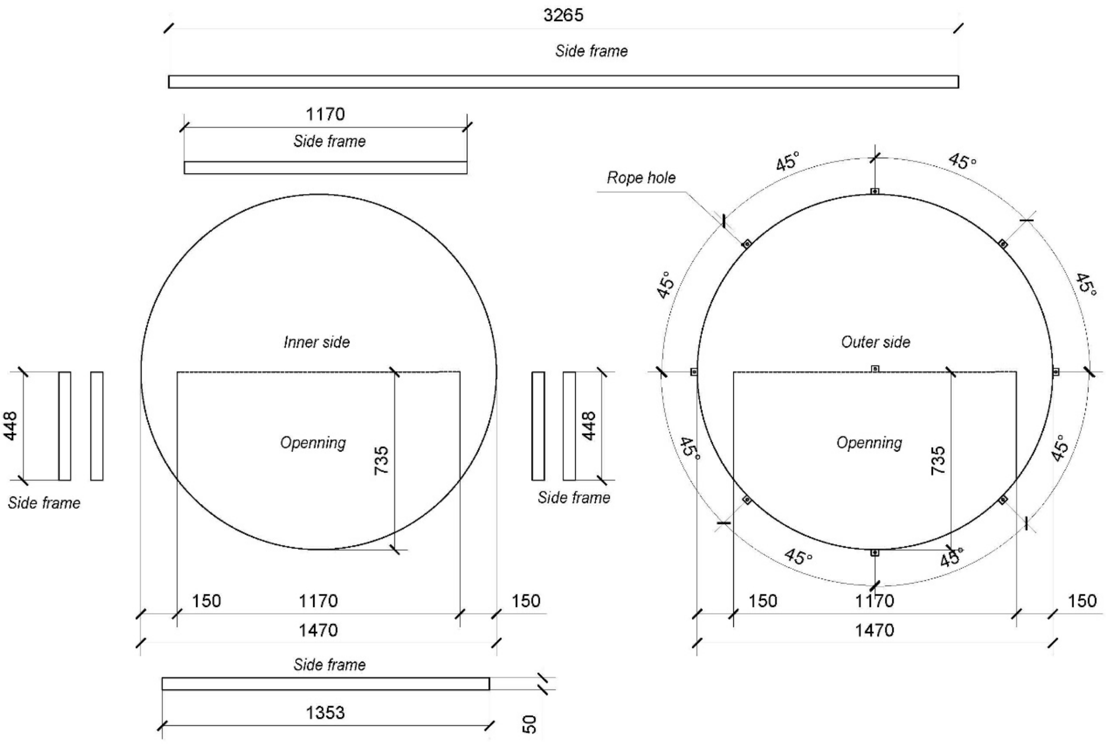


Fig. 3.10 Details of the skylight insulation cover

3.3.2 Selection of materials and manufacturers

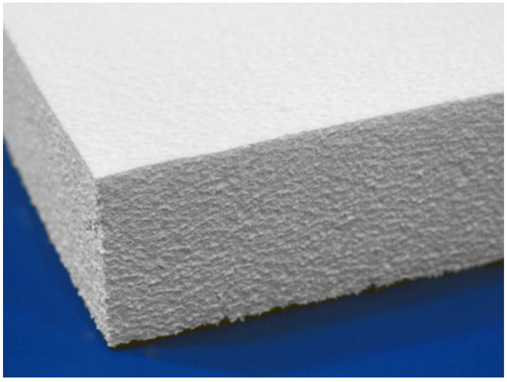
The first sample of insulation panels for the roof and walls were fabricated by a Japanese company that has sufficient experience in manufacturing various thermal insulation covers for high-temperature pipes and plant equipment. This company suggested three types of core materials for insulation panels: molded glass wool, polystyrol, and urethane, as listed in Table 3.1. Among these three materials, molded glass wool was chosen for the sample panel, considering its fire resistance. The sample panel was composed of molded glass wool covered by a flameproof tarpaulin used for outdoor tents. The fabricated roof and wall panels are shown in Fig. 3.11.

The manufacturing price of the Japanese company was too expensive for *ger* insulation improvement. The total price of one wall panel and two roof panels that are manufactured by the Japanese company was equal to that of a new five-walled ger in the Ulaanbaatar market.

Hence, to reduce the price, it was crucial to utilize inexpensive materials available in Mongolia and manufacture products equivalent to the test samples created by the residents.

Therefore, we surveyed the stock of materials for insulation and cover that are locally accessible at an inexpensive price. However, the molded glass wool adopted for the prototype is not widely available in Mongolia; therefore, based on the local availability, we chose extruded polystyrene foam insulation, also called XPS boards, for the wall panels and rolled glass wool was selected for the roof panels to reduce the risk of fire in the case one falls on a coal stove. While considering the fabric to cover the core materials, fire-resistant fabrics were not available in the local market; therefore, we utilized a flameproof fabric purchased in Japan for roof panels. Moreover, the author purchased artificial leather from the local market to cover the wall panels. The color of the fabric chosen was white, which is a standard color inside the *gers*. Locally manufactured insulation panels are shown in Fig. 3.12. The total weight of the entire set of roof panels was estimated to be approximately 80 kg.

Table 3.1 Sample materials for insulation panel from a Japanese manufacturer

Molded glass wool	
Polystyrol	
Polyurethane	

(a) (b) (c) (d)

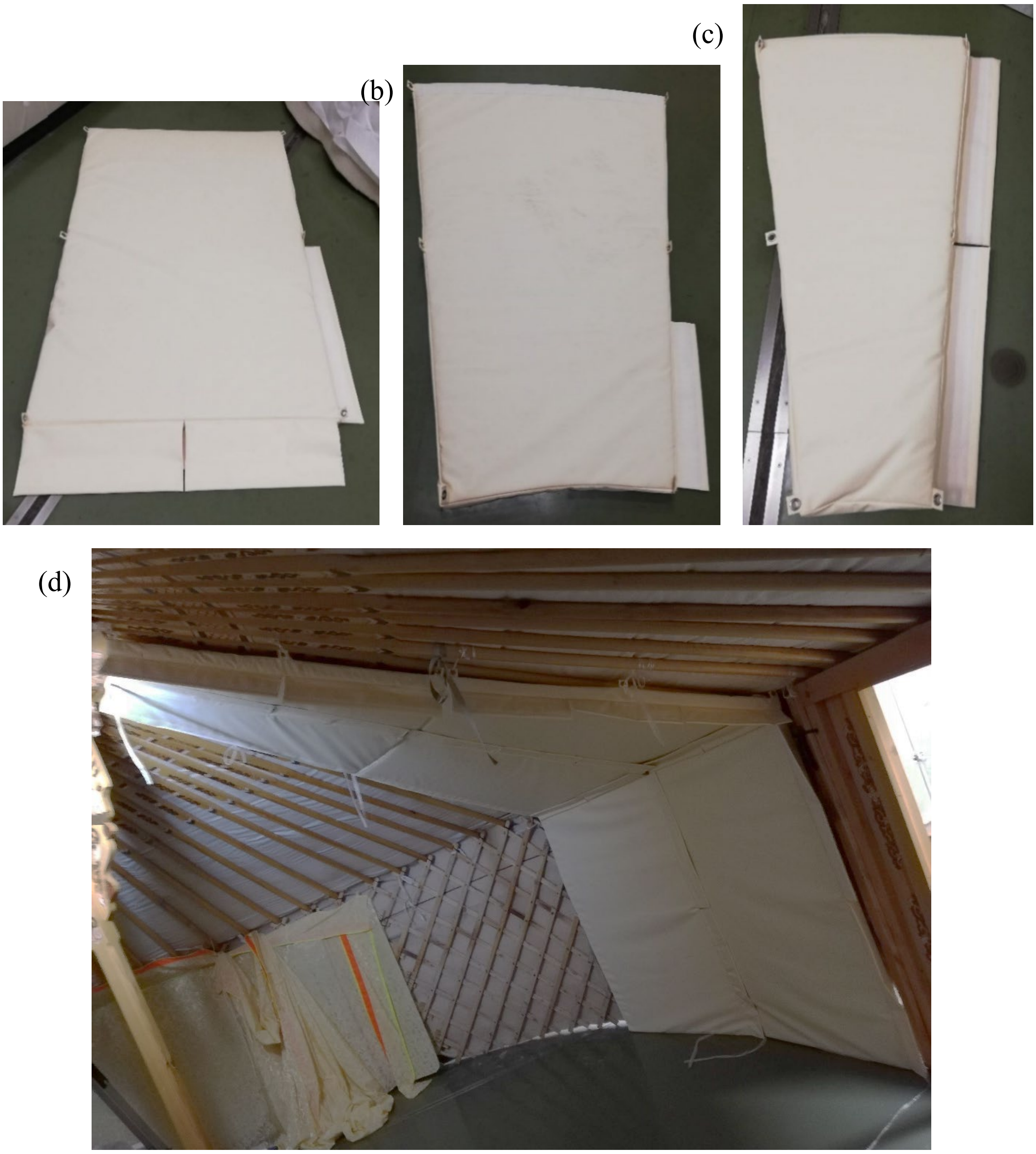


Fig. 3.11 (a) Wall panel sample; (b) Lower roof panel sample; (c) Upper roof panel sample; (d) Samples installed inside a *ger*

Fig. 3.12 Local materials and manufacturing process: (a) Wall cover fabric; (b) Extruded polystyrene foam insulation board for wall panels; (c) Mineral wool for roof panel; (d) (e) Local manufacturing process; (f), (g) Final locally manufactured panels

3.3.3 Windbreak room

Because the *ger* has a single circular room without a toilet, the indoor air temperature rapidly drops when occupants go out from a *ger* to use an outdoor toilet. Specifically, more than 90% of the respondents living in *gers* said that indoor thermal condition in winter is occasionally either too hot or too cold. Therefore, to reduce this sudden temperature drop, a prefabricated windbreak room was developed in consultation with a local carpenter. Fig. 3.13 shows the floor plan and sectional view of the proposed windbreak room. This prefabricated windbreak room is composed of oriented strand board and can be attached to the door of a *ger*. This windbreak room can be easily disassembled when residents dismantle their *ger*.

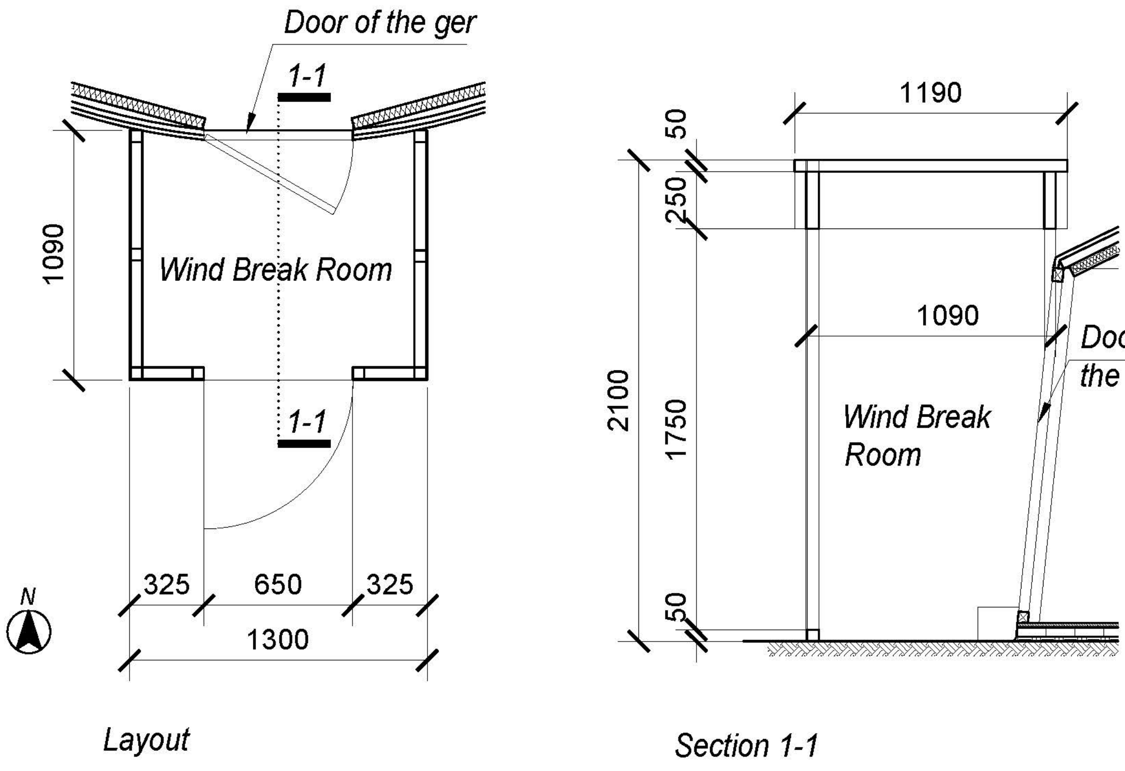


Fig. 3.13 Design of the prefabricated windbreak room

3.3.4 Price of the developed system

The cost of the proposed retrofitting system is summarized in Table 3.2. As of January 2020, at the local market in Ulaanbaatar, the insulation panels materials cost approximately MNT 1,200,000, which is approximately half of the price of a five-walled *ger*. Conversely, the manufacturing cost at a local sewing shop was approximately MNT 700,000, which is approximately 30% of the price of a five-walled ger. The total cost of a prefabricated windbreak room was MNT 350,000, including material and labor costs.

Table 3.2 Cost of retrofitting

Retrofitting components	Cost (MNT)	Cost (USD)
Material of the insulation panel	1,200,000	419
Insulation panel manufacturing	700,000	244
Prefabricated windbreak room	350,000	122

3.3.5 Expected reduction in heating demand

The annual heating load *H* [Wh] was estimated, for a baseline *ger* using the following equation with an assumption of negligible heat loss from the floor.

$$H = \left(AU + \rho c_p Q\right) \cdot DH, \quad (3.1)$$

where *U* is the thermal transmittance of a *ger* envelope [$Wm^{-2}K^{-1}$], *A* is the surface area [m^2] of the *ger* envelope, ρ and c_p are the density [kgm^{-3}] and specific heat [$Jkg^{-1}K^{-1}$] of the air, respectively, and *Q* is the ventilation rate [m^3s^{-1}]. *DH* is the degree hours, estimated to be 8730 °C h based on the weather data of 2019 (*Climate Data Online*).

The estimated monthly heating energy for both a baseline *ger* and a retrofitted *ger* is shown in Fig. 3.14. The assumed U value for the baseline *ger* was 7.5 $Wm^{-2}K^{-1}$, whereas that for the insulated retrofitted *ger* was 2.2 $Wm^{-2}K^{-1}$. Owing to the low U value of the retrofitted *ger* envelope, it can be noted that the insulation-related retrofitting significantly reduced the heating load. In 2018, the Mongolian government and Ulaanbaatar city office introduced a subsidy for nighttime electricity to reduce emissions from coal stoves and to encourage the use of electric heaters in the *ger* districts (*Ulaanbaatar Electricity Distribution Network*). In the case of the baseline *ger*, after replacing a coal stove with an electric heater, the annual electricity cost after implementing the nighttime electricity subsidy was estimated as MNT 2 million. After applying the developed insulation method, the annual electricity cost can be reduced to MNT 0.5 million, which is less than the annual cost of coal used in a *ger*. Note that the estimated cost of annual coal consumption is MNT 741,412 in 2019 (Ulaanbaatar statistics, 2019).

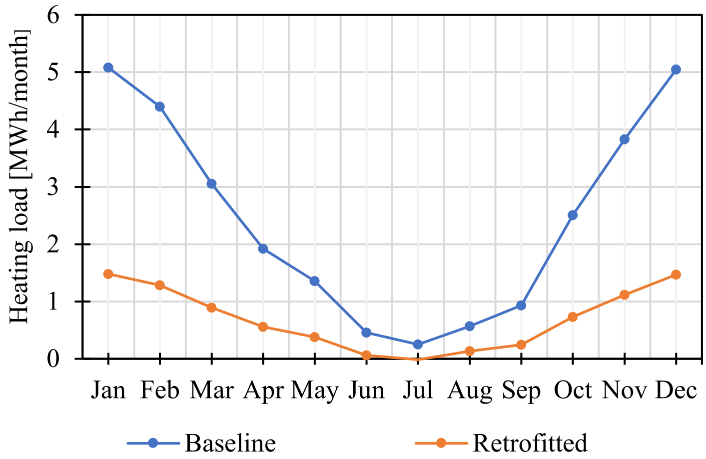


Fig. 3.14 Monthly electricity consumption of baseline and retrofitted *gers*

3.4 Demonstration test of the developed retrofitting method

3.4.1 Retrofitting installation at an urban *ger*

In January 2020, a typical five-walled *ger* located in Songino Khairkhan district (47°58′ N 106°49′ E) of Ulaanbaatar, Mongolia was retrofitted with the developed insulation prototype. The location of the retrofitted *ger* is shown in Fig. 3.15. Fig. 3.16 shows the target *ger* before retrofitting. This baseline *ger* had two layers of felt sheet envelope and the occupants insulated the joint between the wall and the floor with tarpaulin and ground soil as usually done during winters.

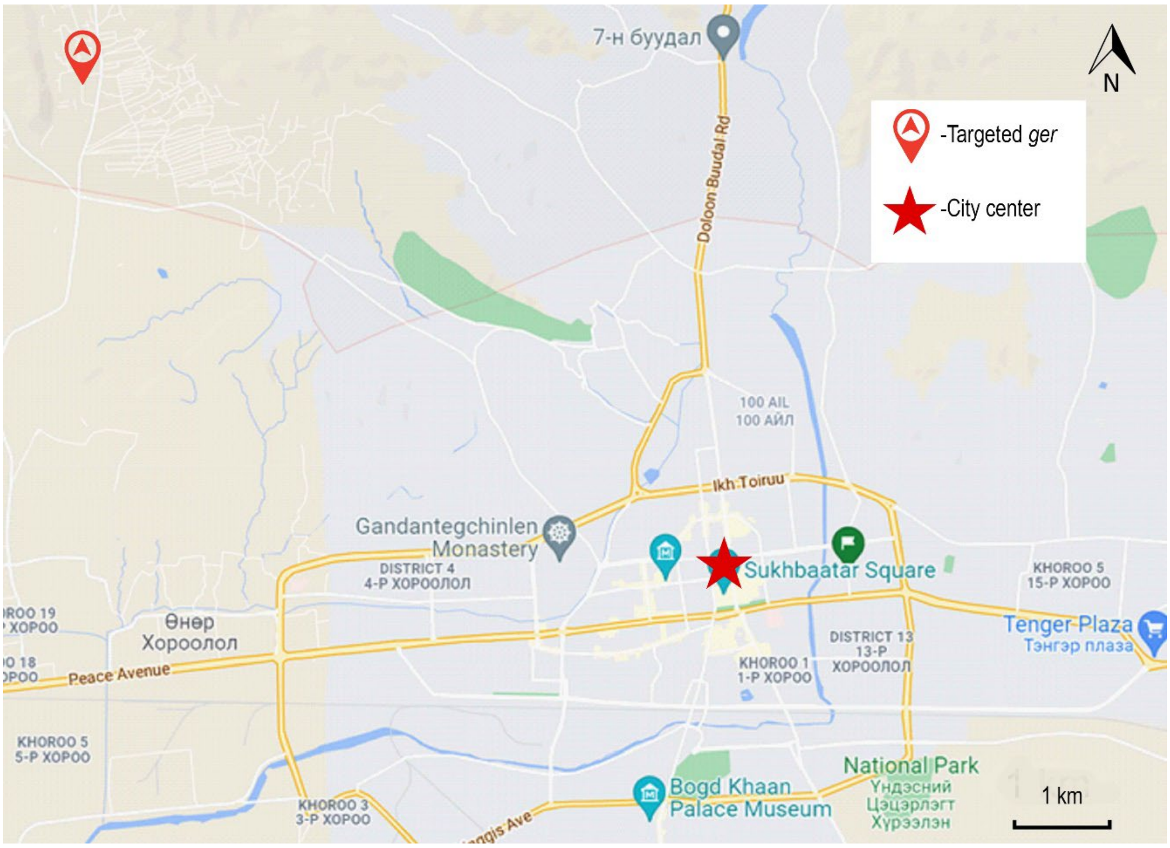


Fig. 3.15 Location of retrofitted *ger* in Ulaanbaatar

The wall panels are first mounted on a lattice frame as shown in Fig. 3.17. Then, the lower panels of the roof are mounted beneath the pillars, as shown in Fig. 3.18; subsequently, the upper panels of the roof are mounted, as shown Fig. 3.19. Fig. 3.10 shows the interior of the retrofitted *ger*. Finally, the insulation panel for the skylight is mounted on the circular frame of the skylight, as shown in Fig. 3.21. The attached windbreak room is shown in Fig. 3.22. Eight hours is required to install the insulation panels on the *ger*, which includes the movement of the furniture by two occupants. In the case of the windbreak room, the carpenters who fabricated the components, assembled and attached the room to the *ger* in 2 h.

Fig. 3.16 Baseline *ger* before retrofitting

Fig. 3.17 Installation of the wall panels

Fig. 3.18 Installation of the lower panels of the roof

Fig. 3.19 Installation of the upper panels of the roof

Fig. 3.20 Retrofitted *ger*

Fig. 3.21 Insulation for the skylight /*toono*

Fig. 3.22 Attached windbreak room

3.4.2 Perception of the occupants and neighboring households toward retrofitting

After the installation of the developed retrofitting system, the perception of the occupant toward retrofitting and the resultant indoor thermal environment of the *ger* was determined. The opinions of the two occupants regarding retrofitting was generally positive. However, this positive evaluation might be not directly attributed to the insulation-related retrofitting because the coal stove was also replaced with electric heaters after the insulation panels were installed. The positive evaluation of the occupants is also probably affected by the white color of the insulation panels, which brightened the interior space. Their satisfaction was higher after the installation of the windbreak room. The occupants started going out to use the toilet wearing indoor clothing such as T-shirts even though the outdoor temperature was approximately -25 °C.

Moreover, the author invited neighboring *ger* residents and local government officials to the retrofitted *ger* to receive their feedback. Their opinions toward the insulation panels, particularly the wall panels, were positive. Some observers suggested that the roof panels could be fitted outside the wooden frame to avoid a falling risk. The local government officer and neighboring households were interested in the cost of the insulation panel materials. Moreover, the local government officer proposed an idea to implement insulation panels for a large number of households. He recommended that, if the government subsidizes the material cost of insulation panels, then sewing can be performed by *ger* residents.

3.5 Conclusion

Gers are traditional nomadic dwellings that are currently used as urban habitats in Mongolia. A *ger* has a few layers of felt sheets and is heated by a primitive coal stove, which results in a large amount of pollutant emission. Therefore, in this chapter, a retrofitting method at a moderate cost was proposed to improve the thermal insulation of the *gers*. The proposed method consists of insulation panels and a windbreak room. The design was aimed to assure affordability by simplifying the manufacturing process and utilizing locally accessible materials. The prefabricated insulation panels can be installed by the residents themselves. Both the insulation panels and the windbreak room do not hinder the regular practice of dismantling and reassembling *gers*.

The idea behind the proposed system is simple: anyone can insulate their *gers* by installing insulation panels that are wrapped with flame-retardant sheets using Velcro. The process is sufficiently simple that, if its impact is widely recognized, then local residents will be able to manufacture and sell the necessary parts as a business. Currently, only one *ger* was used for the demonstration test in this study. To promote this system, further improvement of the retrofitting method is required and large-scale demonstration tests must be performed in several *gers* with the cooperation of the local authorities to raise the awareness regarding the effectiveness of insulation-related retrofitting.

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Chapter 4
Field Measurement of the Indoor Thermal Conditions of Urban *Gers* in Winter

4.1 Introduction

Mongolia is located in the northern part of East Asia; consequently, living spaces must be heating owing to its fridge winter season. Specifically, space heating currently consumes 39.5% of the energy used in households and the commercial sector (Energy Charter Secretariat, 2011). Moreover, 58% of the heating energy of households relies on coal, causing serious air pollution in winter in urban areas (National Statistical Office of Mongolia, 2016b). Considering the statistics that *gers* located in the *ger* districts are the homes of approximately 114,000 urban households in Ulaanbaatar (National Statistical Office of Mongolia, 2016b), prompt actions for both the improvement of indoor thermal environment and reduction of pollutant emission in urban *gers* are urgently required for not only the improvement in living quality but also for solving the current air pollution in the short term. To achieve this, understanding the indoor thermal characteristics of this unique temporary housing is important.

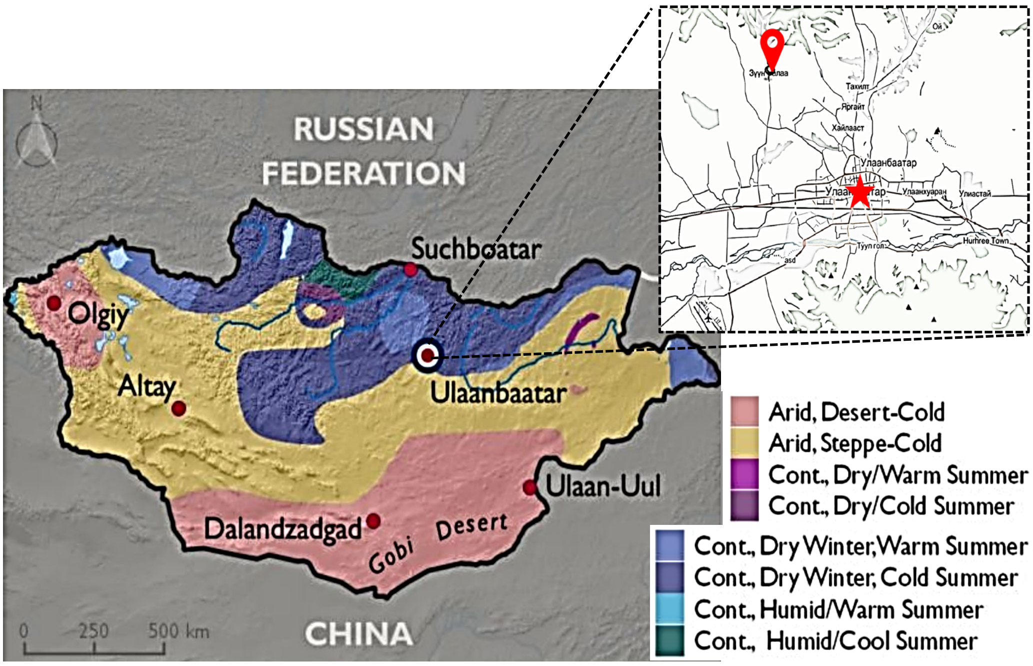
In a previous study on the indoor thermal environment of *gers* that are heated by a stove, Ishikawa et al., (2007) measured the indoor temperature of six *gers* in Ulaanbaatar in winter for three days and reported a large vertical temperature difference owing to the low insulation performance. Buyantogtokh and Zang (2019) measured the indoor temperatures for 10 *gers* for 14 days and estimated the ventilation rates and heat loss coefficients. Bayandelger et al. (2020) conducted a field experiment to assess the feasibility of electric thermal storage utilizing photovoltaics (PV) in a *ger* with additional insulation. They reported the expected reduction in pollutant emission owing to the use of an electric thermal storage heater instead of the conventional coal stove. They also reported that 31% of the energy demand can be supplied by the PV system. Pillarisetti et al. (2019) performed a long-term measurement of the performance of electric air-to-air heat pumps that are tailored to cold climates in self-built detached houses and *gers* for approximately 8 months and reported acceptably moderate performance of the heat pumps. Despite such attempts, the indoor thermal features of current *gers* that are heated by a coal stove have not been well documented in either English or Mongolian.

Consequently, this chapter intends to deepen the understanding of the indoor thermal environment of typical urban *gers* heated by primitive coal stoves in winter based on a field measurement. Furthermore, the demonstration test of the insulation-related retrofitting method developed in Chapter 3 was also conducted during this field measurement. Considering the gradual decline in traditional architectures in various regions owing to economic development and urbanization, the results of this study can provide valuable insights not only from the perspective of environmental engineering but also architectural design and history.

4.2 Methodology

4.2.1 Location

The two *gers* located in the Songino Khairkhan district (47 °58′ N 106 °49′ E) in the northwest outskirt of Ulaanbaatar at a distance of 11 km from the city center were considered for measuring the indoor thermal condition. These *gers* are named *Ger* A and *Ger* B. The location of the investigated *gers is* shown in Fig. 4.1. The two investigated *gers* were located in the same plot. As *gers* have no toilet, the occupants of these *gers* share an outdoor wooden toilet, which includes a pit latrine in the same plot.



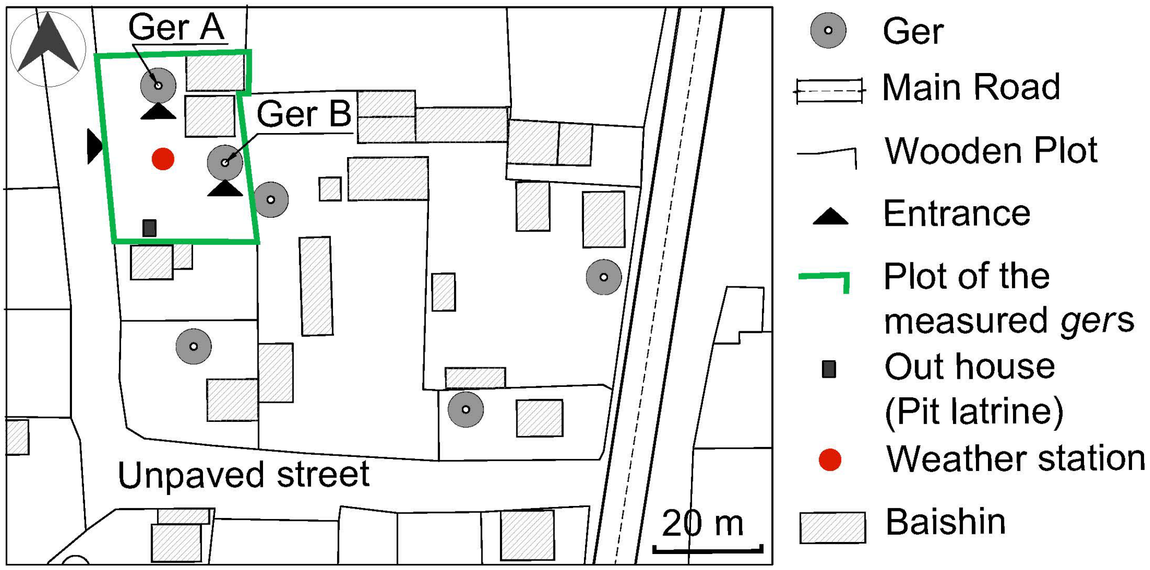


Fig. 4.1 (a) Measurement location on the map showing the Köppen climate classification (*World Maps of Köppen-Geiger climate classification*) (USAID from the American People, 2017); (b) Site plan of the plot in which the surveyed *gers* are located

4.2.2 Measurement period

The measurement was conducted for a period of 30 days from January 18 to February 16, 2020. The entire measurement period was subdivided into three terms, which are named Terms I, II, and III. Table 4.1 lists the conditions of the *gers* for each measurement term.

During the initial 10-day period of Term I, both the *gers* were maintained at baseline conditions, which included the use of coal stoves for heating. The second stage, i.e., Term II, was designed as a comparison experiment between the retrofitted *ger* (*Ger* A) and the baseline *ger* (*Ger* B). To quantify the difference in the heating load between the two *gers*, the coal stove in each *ger* was first replaced with electric ceramic heaters, which enabled the author to monitor the energy consumption directly using smart meters. However, owing to the aged power distribution system of the dwellings, the electric heaters could not be operated at a sufficient output to maintain the room temperature at an appropriate level. Consequently, the electric heaters and coal stove had to be used simultaneously on several days when the outside temperature was low. The last stage, Term III, was for the comparison between *gers* with and without insulation panels after the attachment of a windbreak room.

Table 4.1. Measurement period

Term	*Measurement period*	*Conditions of Ger A*	*Conditions of Ger B*
I	January 18–27, 2020 (10 days)	Baseline *ger* with coal stove for heating The *ger* was fully occupied by at least one occupant on Jan 18 and 26	Baseline *ger* with coal stove for heating The *ger* was fully occupied by at least one occupant on Jan 18 and 26
II	January 28–February 6, 2020 (10 days)	Insulation-related retrofitting of *ger* envelope was performed along with electric heaters The *ger* was fully occupied by at least one occupant on Feb 3 and 5	Baseline *ger* with coal stove heating; partial usage of electric heaters. On Jan 28 and 29, the *ger* was only heated using the electric heating device The ger was fully occupied by at least one occupant on Jan 29 and Feb 4
III	February 6–16, 2020 (10 days)	Insulation-related retrofitting of *ger* envelope + fitment of windbreak room. Electric heaters and a coal stove were used. The ger was fully occupied by at least one occupant on Feb 8 and 14	Baseline *ger* + fitment of windbreak room with coal stove-based heating The ger was fully occupied by at least one occupant on Feb 8 and 14

4.2.3 Conditions of the measured gers

The two *gers* were selected because of their typical features in terms of both the design and materials, which are generally consistent with the specifications of the national standard (Mongolian Agency for Standardization and Metrology, 2003). Table 4.2 lists the specifications of the *gers* and occupants. Fig. 4.2 shows photographs of the exterior and interior of the two baseline *gers*. Fig. 4.3 illustrates the section and layout of the *gers. Gers* A and B were almost identical in size as five-walled *gers*, which is the most popular size according to a national survey (National Statistical Office of Mongolia, 2016b). Both *Gers* A and B insulated their wooden door with one layer of felt sheet covered by a self-made fabric.

Table 4.2. Characteristics of the surveyed *gers*

	***Ger* A**	***Ger* B**
Number of occupants	2	4
Adult	2	1
Children	0	3
Type of *ger*	Five walls	Five walls
Ger volume [m^3]	50.02	47.01
Envelope surface [m^2]	82.33	79.06
Floor area [m^2]	27.5	25.8
Materials of the envelope listed from the outer to inner layers	White fabric Tarpaulin Two layers of wool felt White fabric	White fabric Tarpaulin Two layers of wool felt White fabric
Age of the *ger* [years]	40	2

Fig. 4.2 (a) Exterior of *Ger* A, (b) exterior of *Ger* B, (c) interior of *Ger* A, (d) interior of *Ger* B, (e) *ulzii* stove used in *Ger* A, (f) *khas* stove used in *Ger* B, and (g) electric heaters used in *Gers* A and B during Terms II and III

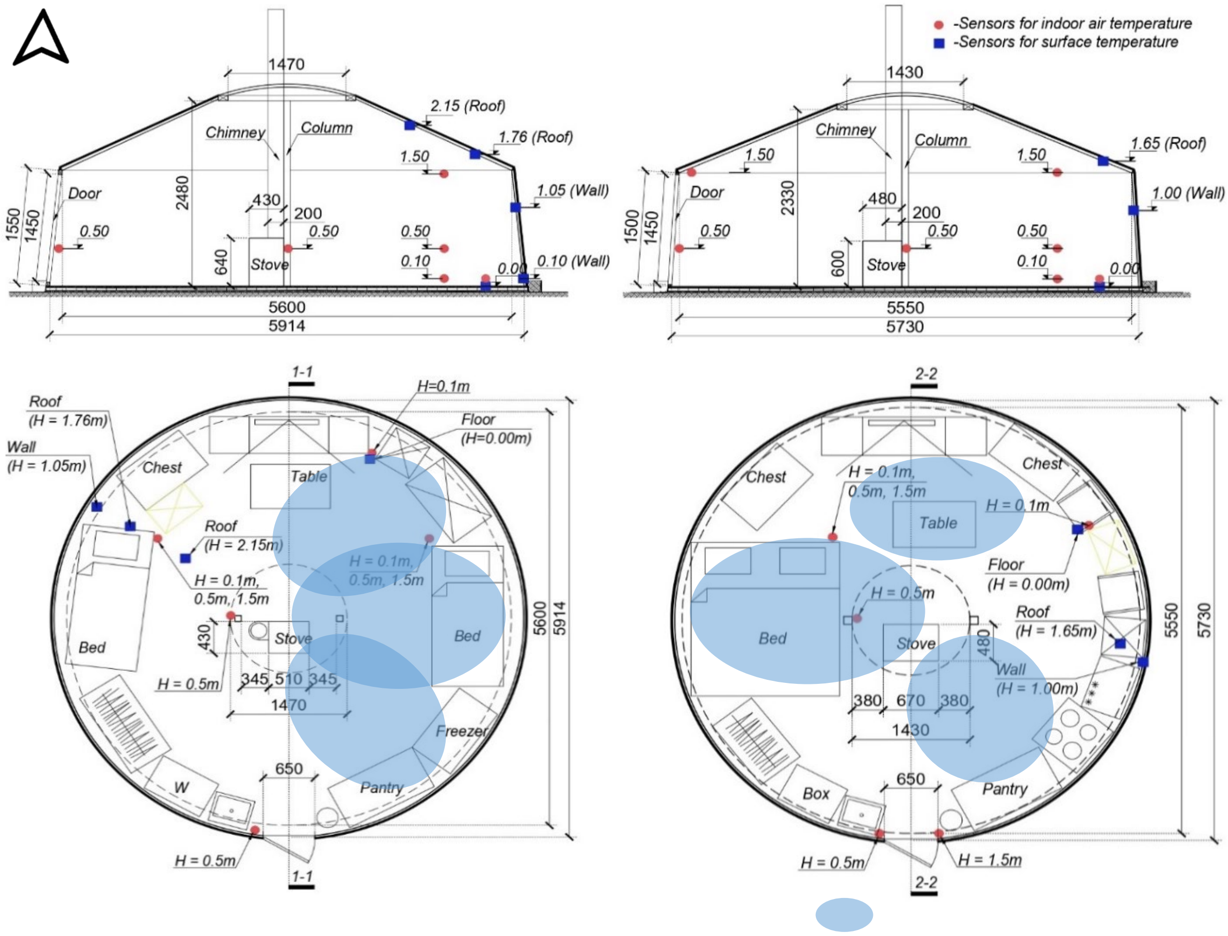


Fig. 4.3 (a) Sectional view of *Ger* A, (b) layout of *Ger* A, (c) sectional view of *Ger* B, and (d) layout of *Ger* B (blue circle indicates the area that are usually occupied by the occupants)

The interior of the retrofitted *Ger* A is shown in Fig. 4.4. The details of the insulation panels are described in Chapter 3. Figs. 4.5 and 4.6 show the windbreak room attached to *Gers* A and B, respectively.

The identification of the heating devices used in the *gers* are listed in Table 4.3. The households of these two *gers* used coal stoves with a top-lit-updraft design. These stoves are commonly called "improved stoves" in Mongolia (Ulaanbaatar Services Improvement Project, 2015). Smokeless fuel was used for both *gers* because the Ulaanbaatar city government had banned the use of raw coal in the city with the introduction of the "smokeless fuel" project(Mongolian State Professional Inspection Agency, 2018). Thermostats were attached to the electric heaters to avoid accidental fires caused by the electrical leakage of aging distribution systems.

Fig. 4.4 Interior of the retrofitted *Ger* A (Terms II and III)

Fig. 4.5 Wind break room attached to *Ger* A (Term III)

Fig. 4.6 Wind break room attached to *Ger* B (Term III)

Table 4.3. Specifications of the heating devices used in the *gers*

	***Ger* A**	***Ger* B**	***Ger* A and B**
Period	Terms I and III	Terms I, II, and III	Terms II and III
Type of heating device	Improved coal stove	Improved coal stove	Two ceramic fan heaters for each *ger*
Model of heating device (Manufacturer)	Ulzii (Royal Ocean LLC)	Khas (Selenge Construction LLC)	MDN-RD114 (Mei Ling Ltd.)
Heating power	6.5 kW	7.5 kW	Two levels (1.6 kW, 3.2 kW) for each heater

4.2.4 Instrumentation

The measuring instruments are listed in Table 4.4. The outdoor temperature (T_{out}), relative humidity (RH), and solar radiation were measured at a height of 2 m inside the plot as the reference weather conditions. The measurement instruments were selected because of their suitable accuracy and low susceptibility to noise in the field during measurement. Note that these instruments are basically similar to those used for previous indoor thermal measurements in buildings (Tuck *et al.*, 2020).

Fig. 4.7 shows the outdoor weather station and indoor thermocouple and thermistor. The indoor air temperature and surface temperature of the *ger* envelope were measured in multiple positions for each *ger*. The measurement positions inside the *gers* are shown in Fig. 4.3. To avoid malfunctions due to low temperature, the data loggers were enclosed in a well-insulated box and equipped with a thermostatic heater. Moreover, at each air temperature measurement position, a T&D thermo recorder (T&D Corporation, Nagano, Japan) was installed. The data measured using the thermocouples and T&D thermo recorders were compared and confirmed their agreement; thus, the data observed by the thermocouples were used for the following analysis.

The electricity consumption of the ceramic fan heaters of the two *gers* was monitored during Terms II and III. The energy monitor used for the measurement is shown in Fig. 4.8. The measurement items were recorded once every minute. In addition, the average daily coal consumption of the *gers* during Term I and the additional coal consumption during Terms II and Term III were determined. During Terms II and III, electric heaters were connected with a thermostat with a setting temperature of 25 °C, which is the maximum level of acceptable temperature according to the specifications of ASHRAE-55 (2010). Fig. 4.9 shows the thermostat used.

Table 4.4. Measuring instruments and accuracy of the sensors

Measurement items	**Sensors and loggers**	**Range and accuracy**
Outdoor air temperature, relative humidity	HOBO U30 Weather Station Data logger & Sensor S-THB-M002 (Onset)	−40 to 75 °C ±0.21 – over 0 to 50 °C
Solar radiation	S-LIB-M003 Silicon Pyranometer (Onset)	±10 W/m^2
Indoor air temperature (9 positions in *Ger* A, 7 positions in *Ger* B)	T-type Thermocouple (ϕ = 0.1mm), Data logger (HIOKI logger LR8432 Z2015-01)	−40 to 125 °C ±0.5 °C
Indoor air temperature (10 positions in *Ger* A, 10 positions in *Ger* B)	TR-52i (T&D)	at −20 to 80 °C Avg.: ± 0.3 °C
Surface temperature (5 positions in *Ger* A, 3 positions in *Ger* B)	T-type Thermocouple (ϕ = 0.1 mm) + data logger (HIOKI logger LR8432 & Z2015-01)	−40 to 125 °C ±0.5 °C
Electricity consumption of heaters (Term I and II, *Ger* B)	Electricity monitor (OWL+USB)	NA

Fig. 4.7 (a) Outdoor weather station; (b) Thermocouple for measuring the indoor air temperature; (c) T&D thermo recorder

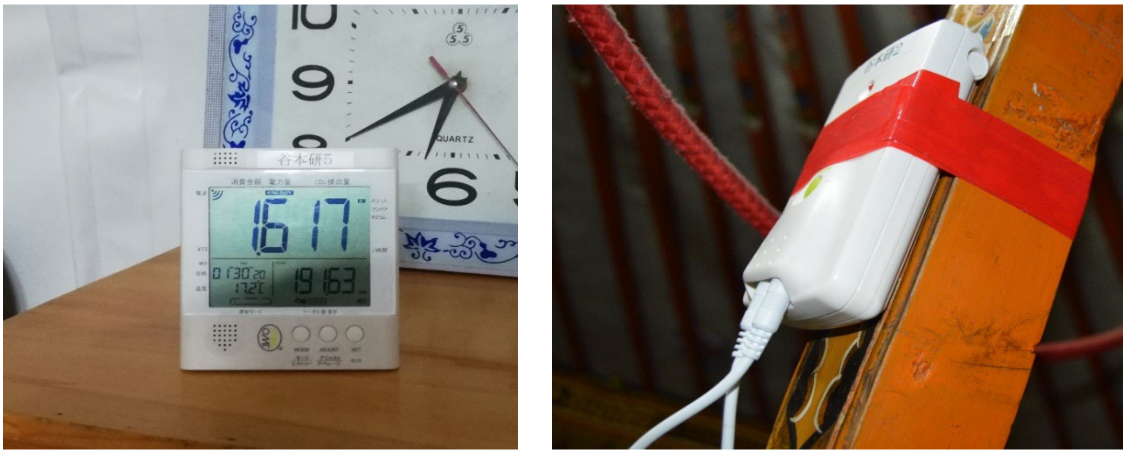


Fig. 4.8 Energy monitor: (a) monitor display and (b) sensor signal transmission

Fig. 4.9 Thermostat connect to the electric heater

4.2.5 Estimation method of the heating power of coal stoves

Assuming a one-dimensional heat transfer through the *ger* envelope, the energy balance can be expressed by the following equations:

$$q + R = \alpha_{out}\left(T_{s,out} - T_{out}\right), \qquad (4.1)$$

$$q + R = \lambda\left(T_{s,in} - T_{s,out}\right)/\Delta x, \qquad (4.2)$$

$$q = \alpha_{in}\left(T_{in} - T_{surf,in}\right), \qquad (4.3)$$

where q is the conduction heat flux [Wm^{-2}]; R is the radiation flux on an internal surface of the *ger* envelope received from the stove [Wm^{-2}]. T_{in} and T_{out} are the indoor and outdoor air temperatures, respectively. $T_{s.in}$ and $T_{s.out}$ are the inner and outer surface temperatures of the *ger* envelop, respectively. α_{in} and α_{out} are the convective heat transfer coefficients [$Wm^{-2}K^{-1}$]; λ is the thermal conductivity [$Wm^{-1}K^{-1}$]; Δx is the depth of the *ger* envelope [m]. By substituting the measured values of T_{in}, $T_{s,in}$, and T_{out}, the heat fluxes q and R can be estimated as shown below.

$$q = \left(T_{s,in} - T_{s,out}\right)/(U^{-1} + U_{out}^{-1}), \quad (4.4)$$

$$R = U_{out}\left(T_{s,in} - T_{s,out}\right) - q, \quad (4.5)$$

$$\text{where } U^{-1} = \frac{1}{\alpha_{in}} + \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{out}}. \qquad (4.6)$$

$$U_{out}^{-1} = \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{out}}. \qquad (4.7)$$

The author assumed α_{in} = 5 W/(m^2K), α_{out} = 10 W/(m^2K), Δx = 0.03 m, λ = 0.127 W/(m K) to estimate the U values.

The estimated radiation flux on a surface of the *ger* envelope can be exchanged to the radiation flux on the normal plane of the vector from a stove to the measurement point of an indoor surface in the *ger* as follows.

$$R_{\circ} = Rcos\theta \quad (4.8)$$

If the radiation from a stove can be assumed to be omnidirectional radiation from a point source, the radiative heating power of a stove H_{stove} [W] can be obtained by surface integration of a hemisphere.

$$H_{stove} = 2\pi L^2 R_{\circ} \quad (4.9)$$

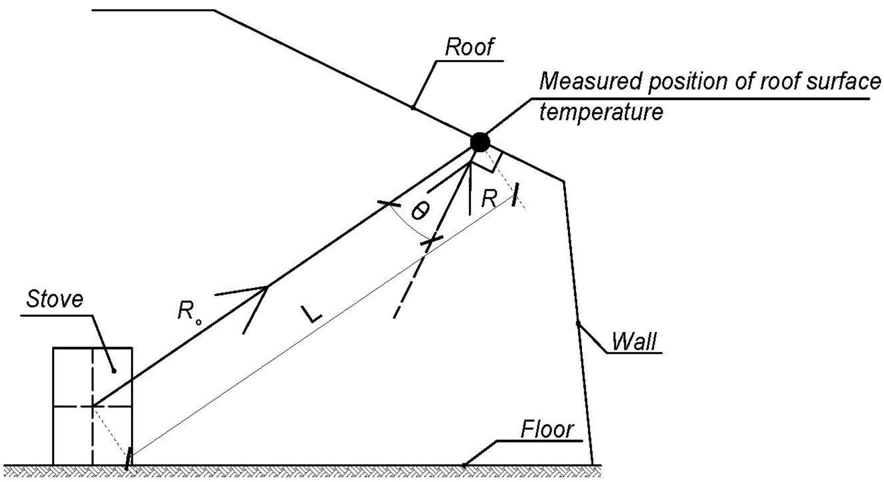


Fig. 4.10 Schematic diagram for estimating the radiation heating power of a stove

4.2.6 Estimation of mean radiant temperature and operative temperature

To analyze the thermal exposure of the occupants, the MRT (T_r) was calculated based on the measured surface temperature of the *ger* envelopes and estimated radiation energy of the stove. In this calculation, the radiation generated by the stove that is received by the body of the occupant was estimated assuming an omnidirectional emission from the stoves and based on the shape factors for a seated occupant that was provided by Dunkle (1963). The distance between an occupant and a stove was assumed to be 1.5 and 1.0 m for *Gers* A and B, respectively, considering the layout of the furniture and the lifestyle of the occupants. The emissivity of the body of the occupant and the *ger* envelope was assumed to be 1.0.

Assuming that a stove is a point source and the human body is a rectangular panel, the shape factor (F_{so}) can be calculated as

$$F_{so} = \left[\frac{1}{2\pi}(\tan^{-1} X - \frac{1}{\sqrt{Y^2+1}}\tan^{-1}\frac{X}{\sqrt{Y^2+1}})\right]2, \qquad (4.10)$$

where X is one-half of the human body width when compared to the distance to the stove and Y is the human body height when compared to the distance to the stove.

If nonuniformity of the surface temperature is negligible and can be modeled by the average of all measured surface temperatures, the radiation heat gain of an occupant Q_o can be expressed as

$$Q_o = \sigma T_{s.ave}{}^4 A_{human} + F_{so} H_{stove}, \qquad (4.11)$$

where A_{human} is the human body surface (=1.6 m^2), $T_{s.ave}$ is the average of all measured surface temperatures [K]. σ is the Stephan–Boltzmann constant (= 5.67x10^{-8} W $m^{-2}K^{-4}$). Therefore, the MRT is expressed as follows:

$$T_r = \left[\frac{Q_o/A_{human}}{\sigma}\right]^{\frac{1}{4}} - 273.15, \qquad (4.12)$$

where T_r is the MRT [ºC].

When evaluating the indoor thermal comfort, predicted mean vote (PMV) (ASHRAE, 2017), which is derived based on the energy balance of a human body by using four environmental variables (air temperature, humidity, radiant temperature, and wind speed) and two occupant-related variables (metabolic rate and clothing insulation), has been widely used for decades, especially for assessment in air-conditioned enclosed spaces. Conversely, it has been reported that, in naturally ventilated rooms and environments where occupants have high flexibility in terms of the thermal adaptation behaviors, the PMV does not always correspond to the thermal sensation of people (Brager and de Dear, 1998). The surveyed *gers* were heated by a stove;

thus, they cannot be classified as naturally ventilated rooms. However, the envelopes of the baseline *gers* were not well insulated and airtight; moreover, the occupants were exposed to the cold outdoor environment every time they went outside to use the toilet, resulting in sudden drops in the room temperature. Therefore, this situation is substantially different from that of a modern air-conditioned room. Moreover, the metabolic rate of the occupants varied according to various activities such as eating and sleeping, and they demonstrated a high flexibility in thermal adaptation behaviors. Considering such features, for estimating the current thermal conditions, the operative temperature T_{op} expressed in the following equation was used instead of the PMV.

$$T_{op} = (T_r + T_{in-0.5})/2, \quad (4.13)$$

where $T_{in-0.5}$ is the spatially averaged indoor air temperature at a height of 0.5 m.

4.3. Results of field measurements

4.3.1 Climate conditions

The outdoor weather conditions and spatial averages of the indoor air temperature of the two *gers* during Terms I, II, and III are shown in Figs. 4.11, 4.12, and 4.13, respectively. In Term I, the insulation retrofitting panels were installed to *Ger* A on January 27; consequently, the indoor air temperature data of *Ger* A was excluded on this day. The outdoor temperature showed a periodic diurnal cycle, ranging between 6 and −30 °C and the daily maximum and minimum values for each day differed marginally. During Term I, the last five days showed relatively high daily maximum temperatures. In the middle of Term II, the outdoor air temperature became marginally lower. Throughout Term III, the overall outdoor air temperature was marginally higher. As expected, the overall outdoor RH showed the opposite trend as the air temperature, ranging from 38 to 92%. The solar radiation data were not available during half of Term I owing to technical issues and the remaining days indicated symmetric daily variation, suggesting clear sky conditions.

Owing to space heating, the indoor air temperature of the two *gers* were always higher than the outdoor temperature, and the difference between the indoor and outdoor temperatures ranged from 15 to 47 °C. The overall temperature of *Ger* B was marginally higher than that of

Ger A and the minimum indoor air temperatures of *Gers* A and B were 2 and 5 °C, respectively, whereas the maximum temperatures were 32 and 30 °C, respectively.

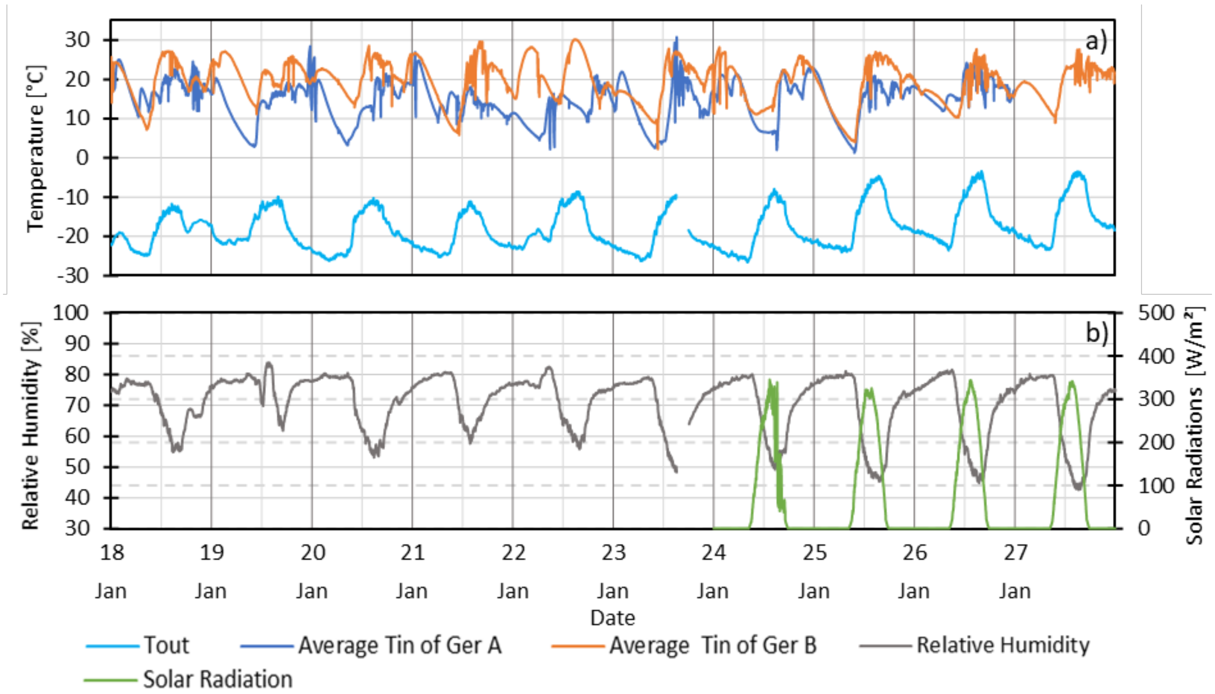


Fig. 4.11 Temporal variations in (a) outdoor air temperature (T_{out}) and spatial average of the indoor air temperature (T_{in}) of *Gers* A and B, (b) relative humidity (RH) of outdoor air environment and global solar radiation for Term I

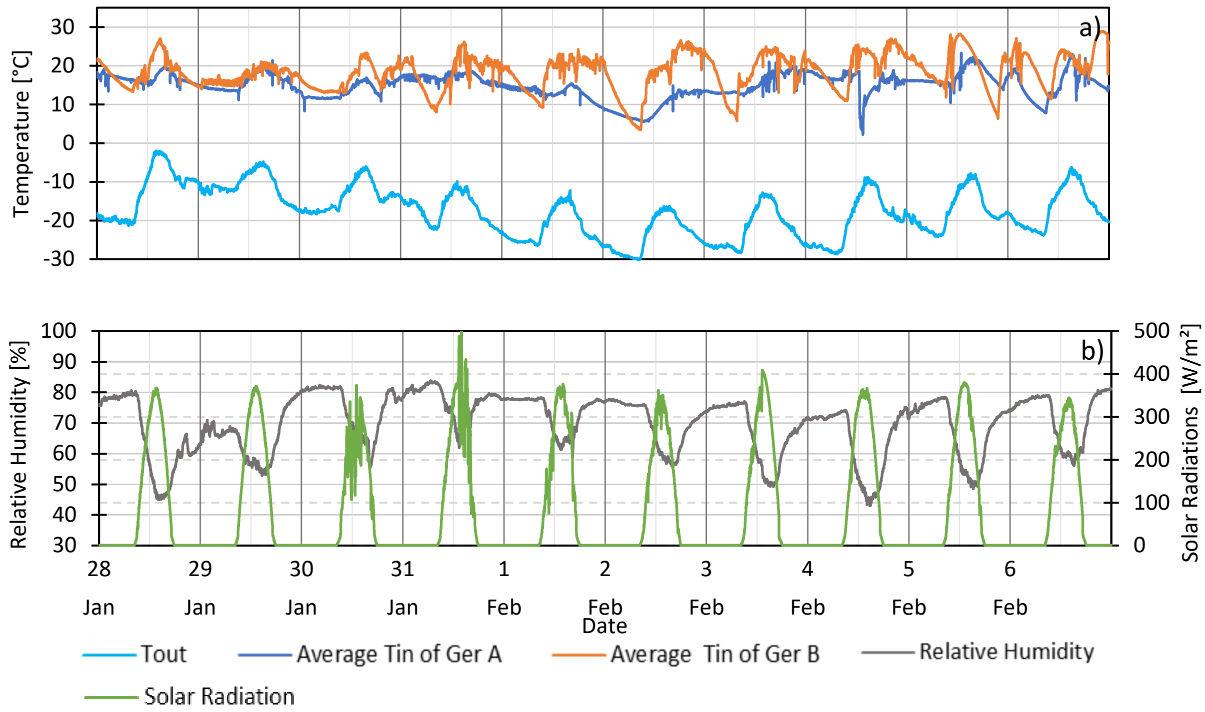


Fig. 4.12 Temporal variations in (a) outdoor air temperature (T_{out}) and spatial average of the indoor air temperature (T_{in}) of *Gers* A and B, (b) RH of outdoor air environment and global solar radiation for Term II

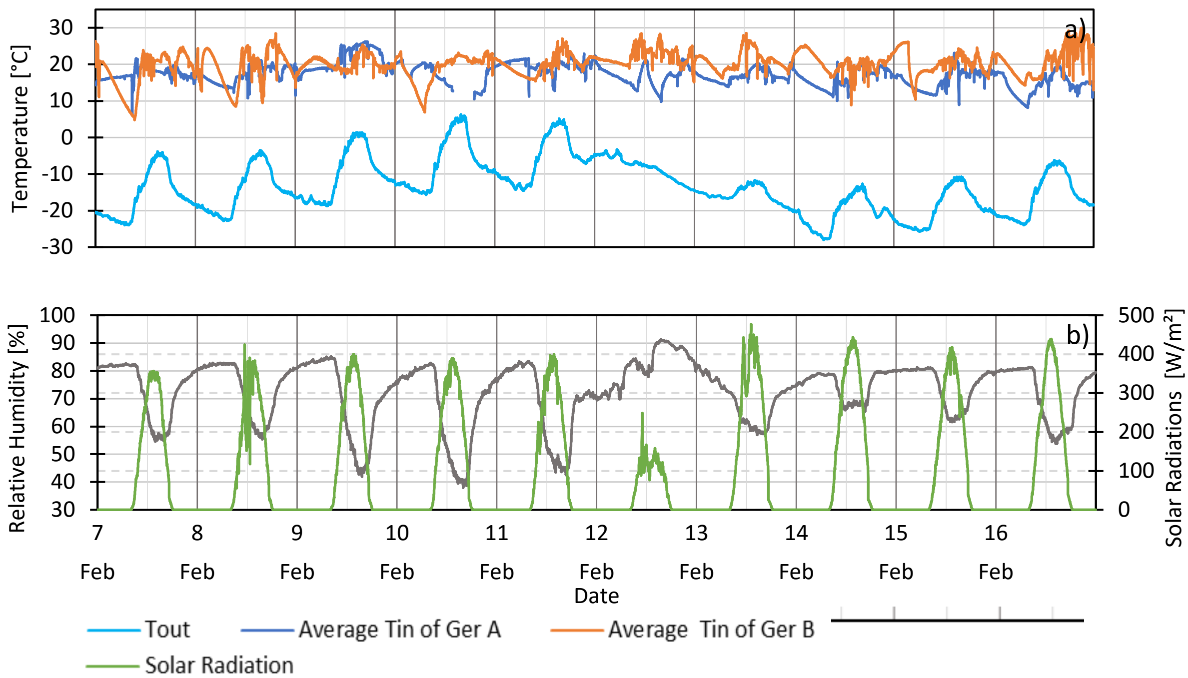
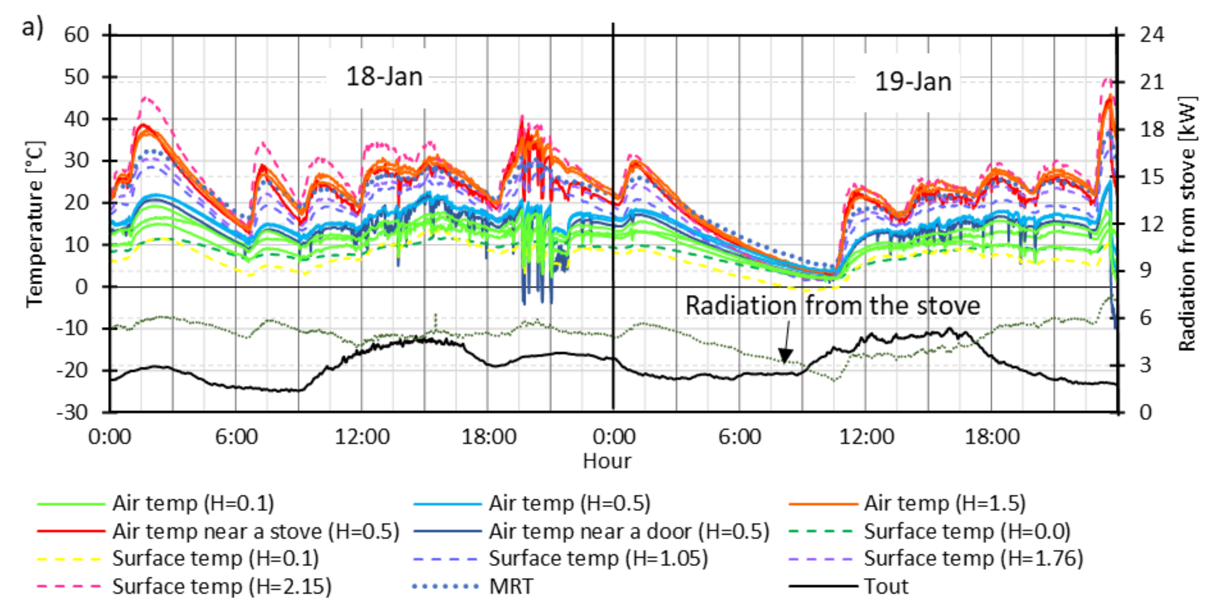


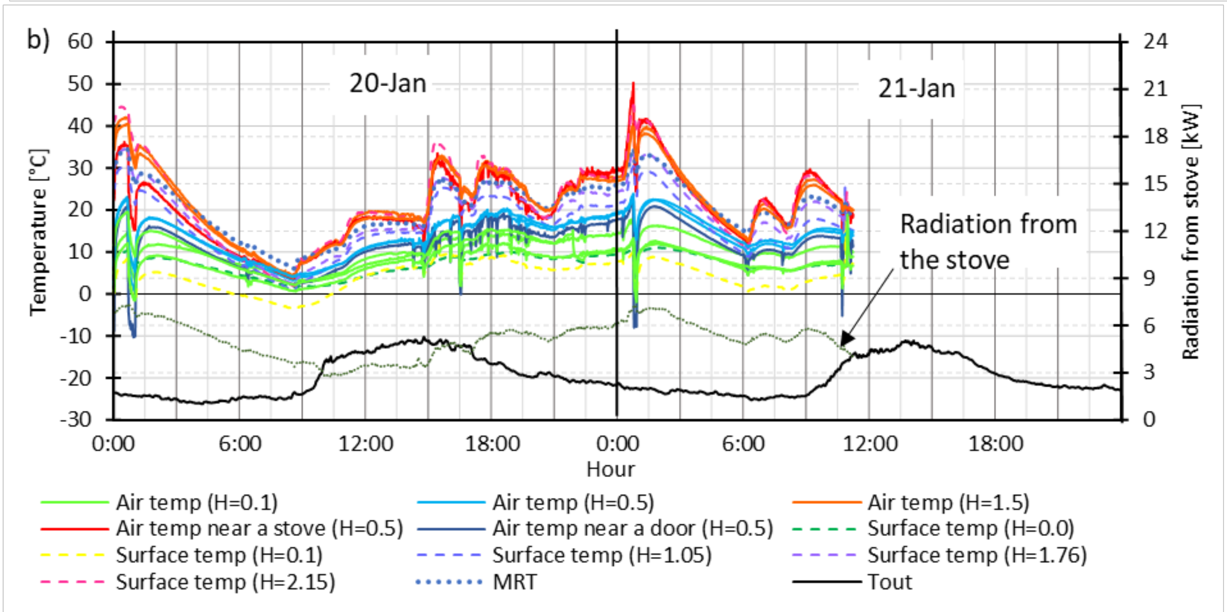
Fig. 4.13 Temporal variations in (a) outdoor air temperature (T_{out}) and spatial average of the indoor air temperature (T_{in}) of *Gers* A and B, (b) RH of outdoor air environment and global solar radiation for Term III

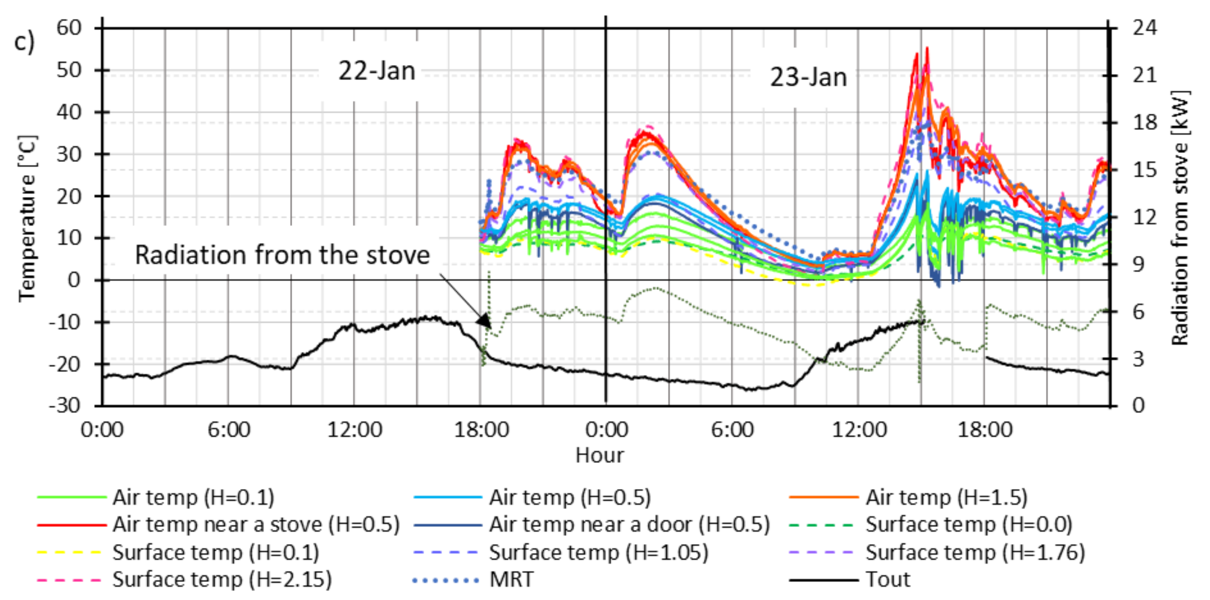
4.3.2 Detailed temporal patterns of the indoor temperature in Term I

Figs. 4.14 and 4.15 shows the indoor air and surfaces temperatures that were observed at various positions in *Gers* A and B during Term I, respectively. As previously mentioned, the data from January 27 was excluded for *Ger* A because the retrofitted panels were installed in *Ger* A on this day. The estimated radiation energy of stoves was also included. Note that at least one occupant always stayed at both *Gers* A and B on January 18 and 26.

When the indoor space was heated by the coal stove, the measured indoor air and surface temperatures of *Gers* A exhibited fluctuating patterns with the same time cycle of 3–9 h. Such fluctuating patterns with multiple peaks in a day varied from the diurnal cycles of both the outside air temperature and solar radiation, which exhibited a single peak. Each day, the daily temperature peak occurrence and fluctuation was different depending on action of the occupant of adding fuel to the burning stove several times a day. This implies that the behavior of the occupants of adding coal occurred at a frequency equivalent to the 3–9 h fluctuating time cycle. The largest indoor air temperature fluctuation occurred at measurement position levels that were 1.5 and 0.5 m near the stove with temperature fluctuations between 3 and 40 °C, while the measurement point at the level of 0.1 m exhibited the smallest range in the temperature fluctuation between −3 and 19 °C. The temperature near the door reveals sudden drops, which are primarily caused by the opening of the door when the occupants enter or exit the *ger*. Conversely, on the nights of January 20 and 21 and the afternoon of January 26, when the indoor temperature become too high, the occupants continuously opened the doors approximately 30 min–1 h to ventilate the *ger* and decrease the indoor air temperature to avoid overheating. The wall and roof surface temperatures were similar to the indoor air temperature, which was caused by the strong radiation emitted from the stove.


a)
18-Jan
19-Jan
Radiation from the stove
Temperature [°C]
Radiation from stove [kW]
Hour
60
50
40
30
20
10
0
-10
-20
-30
24
21
18
15
12
9
6
3
0
0:00
6:00
12:00
18:00
0:00
6:00
12:00
18:00
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout


b)
20-Jan
21-Jan
Radiation from the stove
Temperature [°C]
Radiation from stove [kW]
Hour
60
50
40
30
20
10
0
-10
-20
-30
24
21
18
15
12
9
6
3
0
0:00
6:00
12:00
18:00
0:00
6:00
12:00
18:00
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout


c)
22-Jan
23-Jan
Radiation from the stove
Temperature [°C]
Radiation from stove [kW]
Hour
60
50
40
30
20
10
0
-10
-20
-30
24
21
18
15
12
9
6
3
0
0:00
6:00
12:00
18:00
0:00
6:00
12:00
18:00
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout

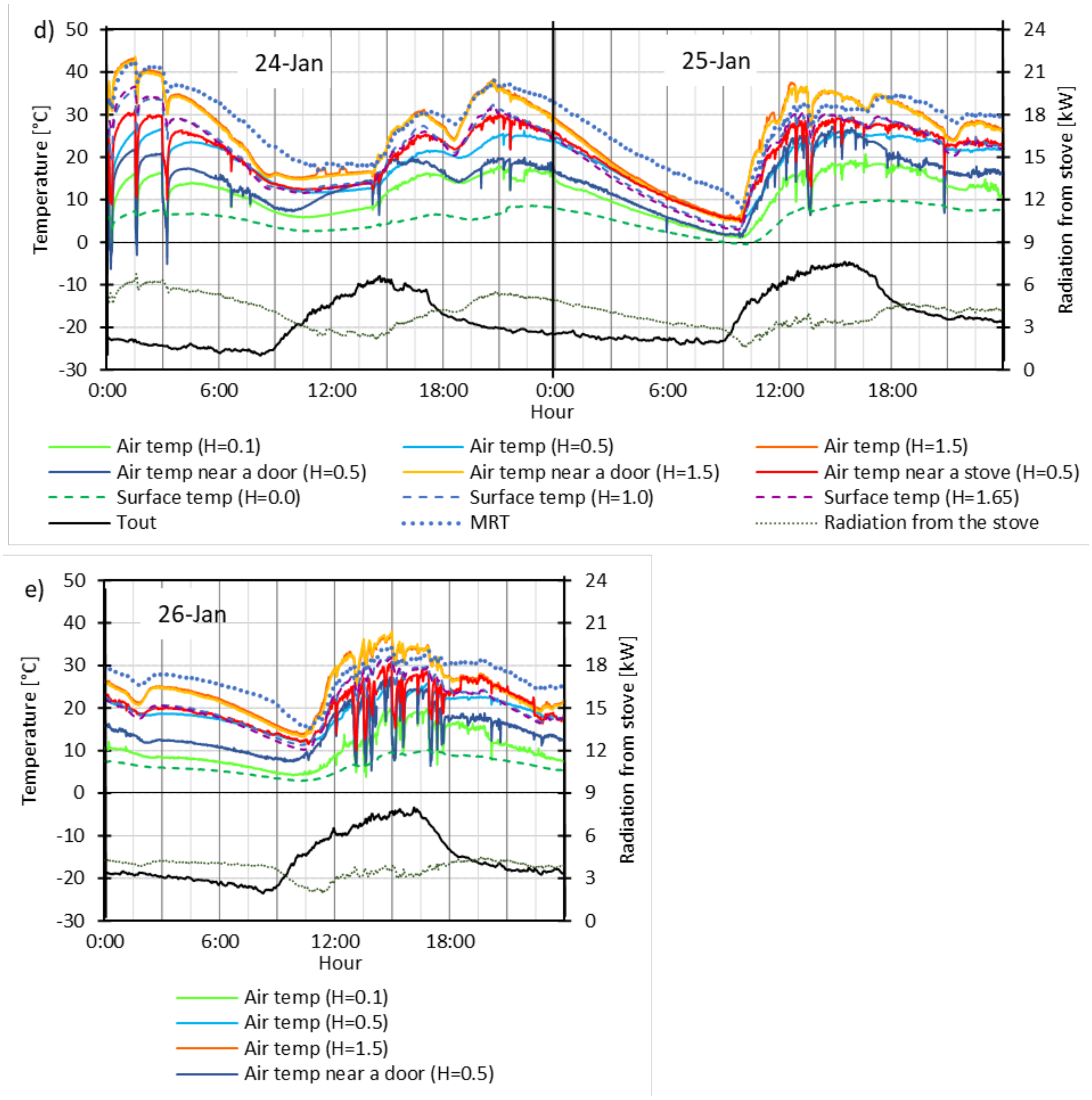
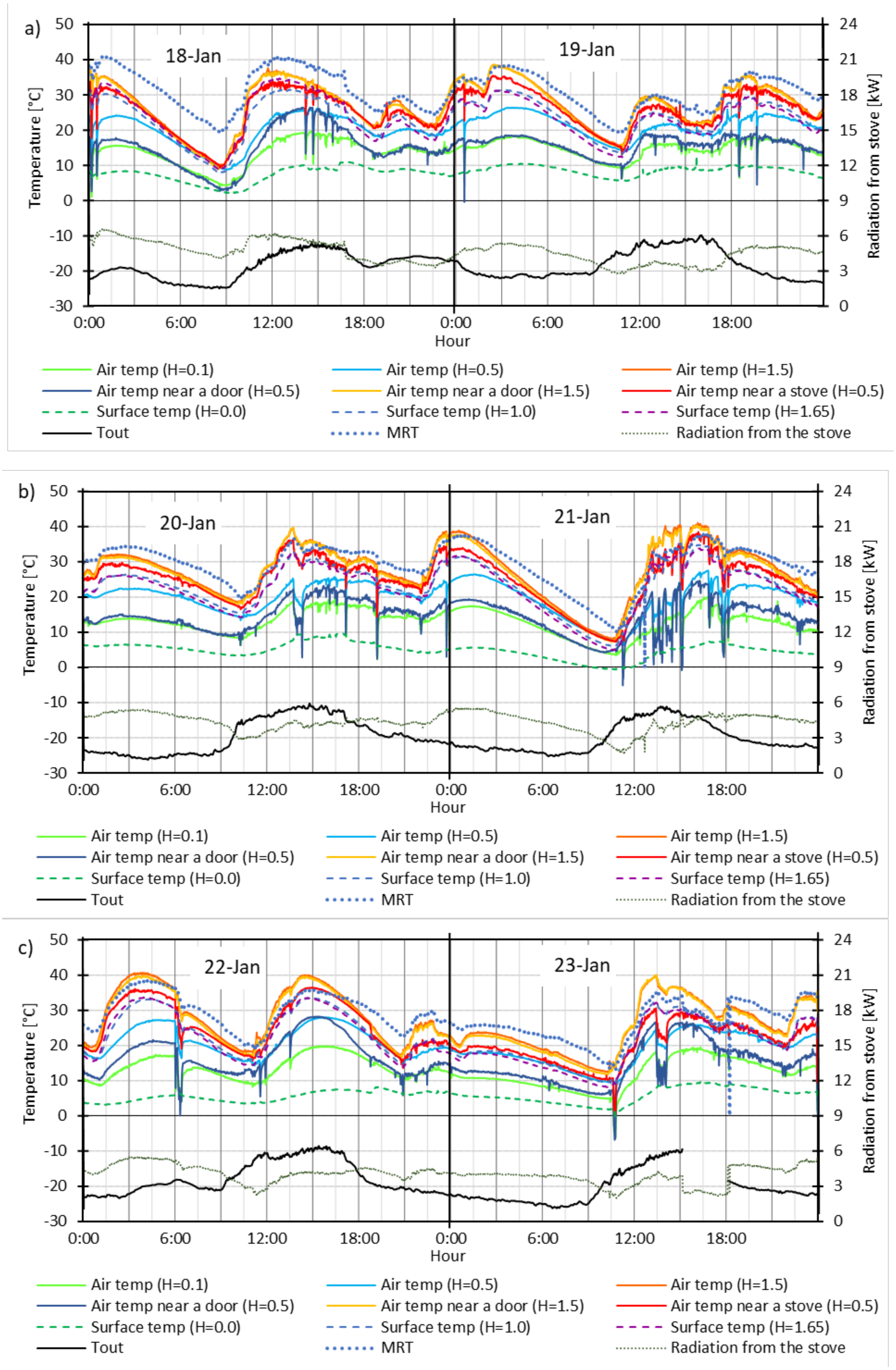


Fig. 4.14 Air and surface temperatures at various positions inside *Ger* A during Term I


a)
18-Jan
19-Jan
b)
20-Jan
21-Jan
c)
22-Jan
23-Jan
Temperature [°C]
Radiation from stove [kW]
50
40
30
20
10
0
-10
-20
-30
24
21
18
15
12
9
6
3
0
0:00
6:00
12:00
18:00
0:00
6:00
12:00
18:00
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a door (H=0.5)
Air temp near a door (H=1.5)
Air temp near a stove (H=0.5)
Surface temp (H=0.0)
Surface temp (H=1.0)
Surface temp (H=1.65)
Tout
MRT
Radiation from the stove

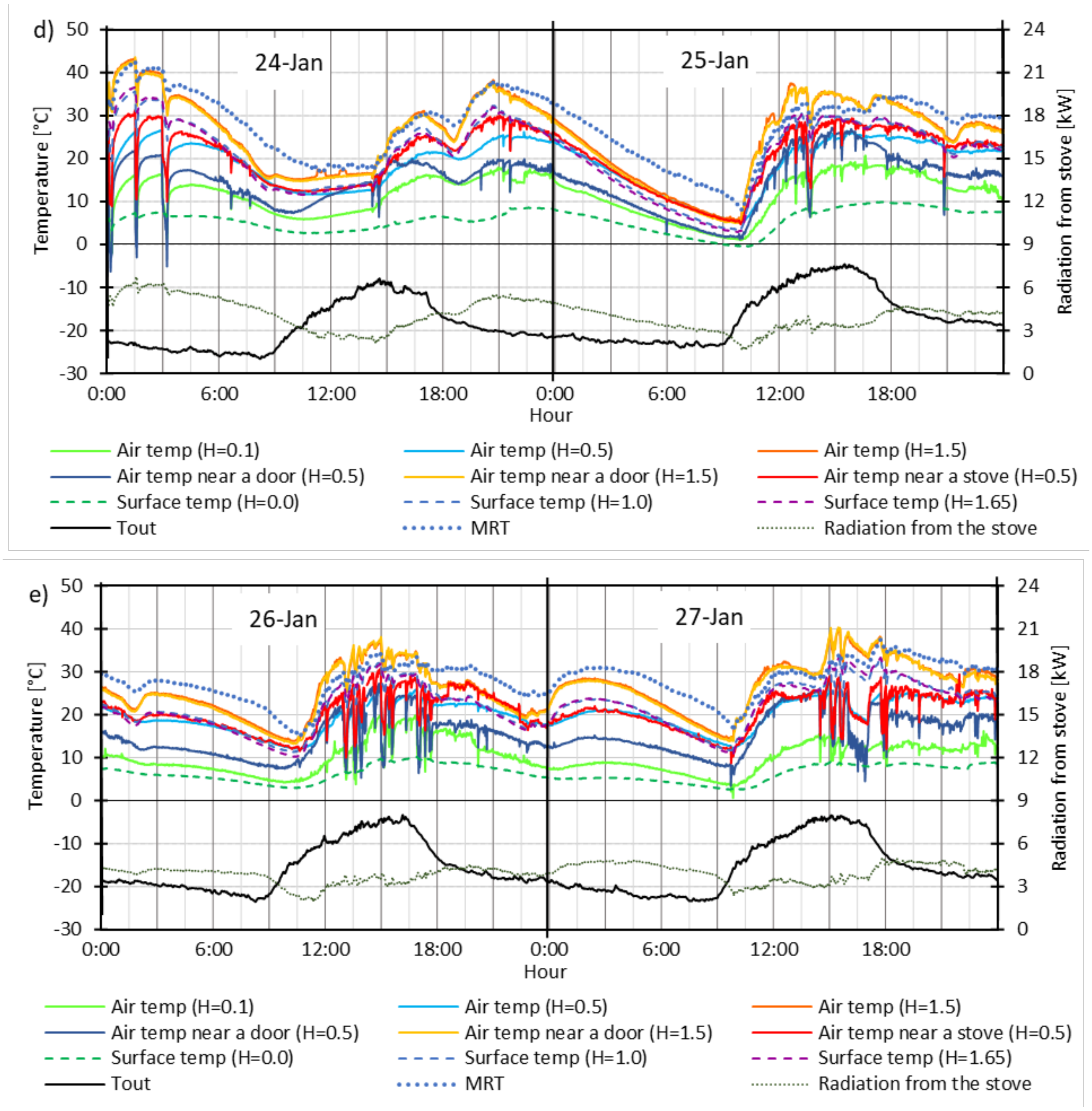


Fig. 4.15 Air and surface temperatures at various positions inside *Ger* B during Term I

4.3.3 Detailed temporal patterns of the indoor temperature during Terms II and III

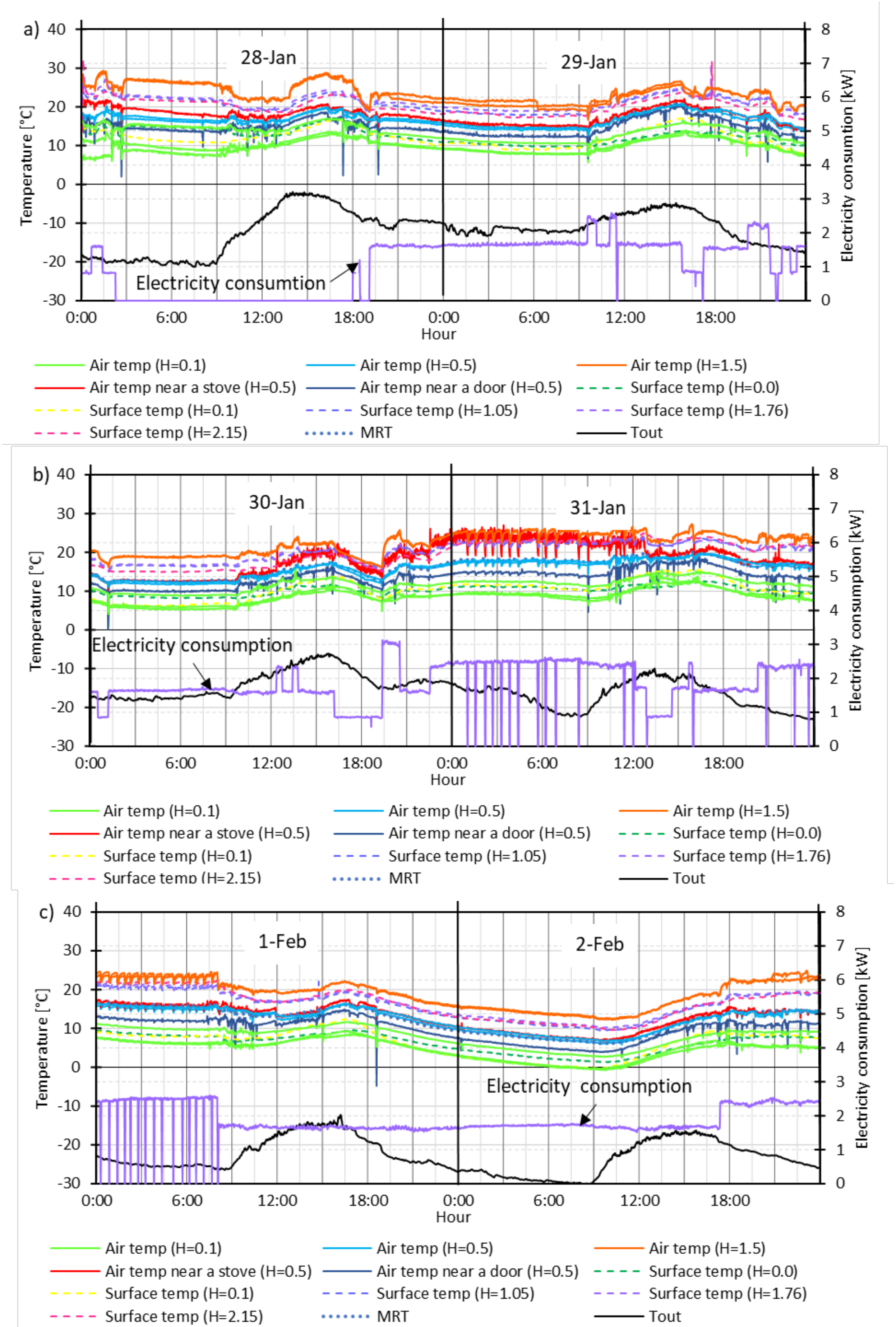
Figs. 4.16, 4.17, 4.18, and 4.19 show the temporal patterns of the indoor temperatures for *Ger* A and *Ger* B during Terms II and III.

Ger A was retrofitted with insulation panels on January 27. This renovation work started at 10 a.m. and was completed at 10 p.m. The coal stove was replaced by electric heaters on the same day at around 10 p.m. Electricity consumption of January 28, February 6 and 7 were not recorded owing to technical issues.

During Term II, *Ger* A was always occupied by at least one resident on February 3 and 5 and occupants stayed at *Ger* B throughout the day on January 29 and February 4. During Term III, both *Ger* A and B were fully occupied on February 8 and 14.

Although the electric heaters were used from10 p.m. on January 27 at both the *gers*, the coal stoves were still hot and emitting radiation. Therefore, the indoor air temperature fluctuated marginally at the beginning of January 28. Although space heating became stable owing to the electric heating, the daytime indoor air temperature increased marginally when compared to the nighttime temperature owing to the outdoor diurnal cycle. From January 29, the thermostat of the electric heater' was set at 25 °C. It should be noted that electric heaters were not used at maximum capacity in both the *gers* because of a poor connection and insufficient power supply limit. Therefore, from February 7, the coal stove was used in addition to the electric heaters in *Ger* A, and the indoor air temperature exhibited daily multiple peaks similar to that during Term I. Further, during this period, the occupants opened their doors more frequently to avoid overheating when compared to the period with only electric heating. The door was usually opened when the stove was used for space heating, which indicates that the stove caused excessive heating. Owing to the simultaneous use of two types of heating devices, calculating the radiation from the stove was not possible; consequently, only the electricity consumption was recorded.

Fig. 4.12 shows the measurement parameters of *Ger* B. While the *ger* was heated by a coal stove, the indoor environment shows a similar tendency as that of *Ger* A. However, the time scale of indoor air temperature fluctuations in *Ger* B was greater than that of *Ger* A. The occupants in *Ger* B explained that they tended to add a large amount of fuel at one time and then not add fuel until the fuel was completely burned out. On January 28 and 29, this baseline *ger* was heated using only electric heaters; however, because of the poor electrical connection, the electric heaters could not be operated at full heating capacity. Therefore, from January 30, the occupants were again using the coal stove predominantly, and the electric heaters were used as auxiliary heat sources. Because the two heating devices were used simultaneously, the radiation from the stove was not calculated and the electricity consumption was recorded during this term. Similar to the case of *Ger* A, from February 7 till the end of the measurement period, a windbreak room was attached at the door of the *ger*. When the coal stove and electric heaters were used simultaneously, the occupants opened their door more frequently to reduce the indoor air temperature.


a)
28-Jan
29-Jan
Electricity consumtion
Temperature [°C]
Electricity consumtion [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout
b)
30-Jan
31-Jan
Electricity consumption
Temperature [°C]
Electricity consumption [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout
c)
1-Feb
2-Feb
Electricity consumption
Temperature [°C]
Electricity consumption [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout

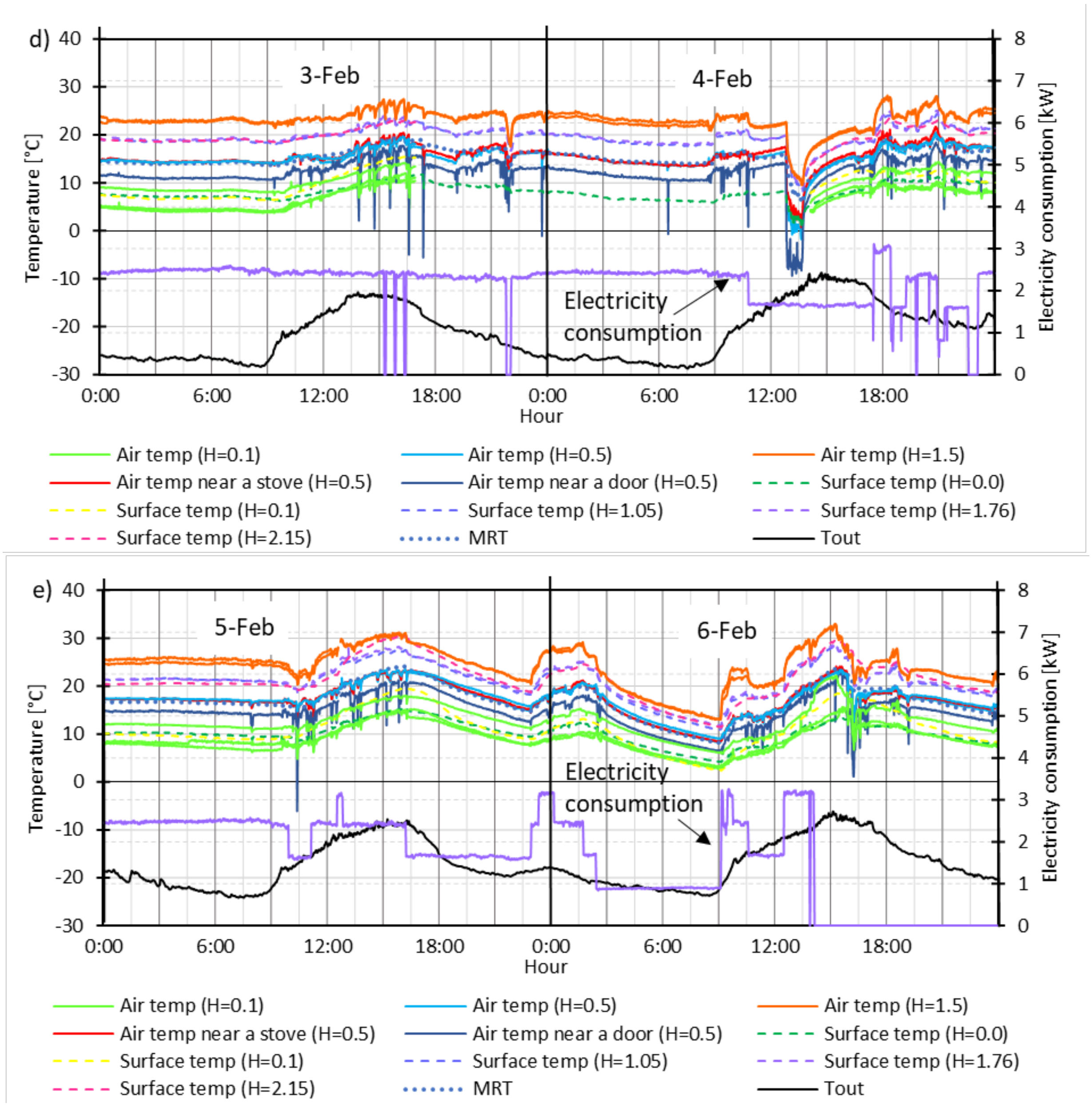
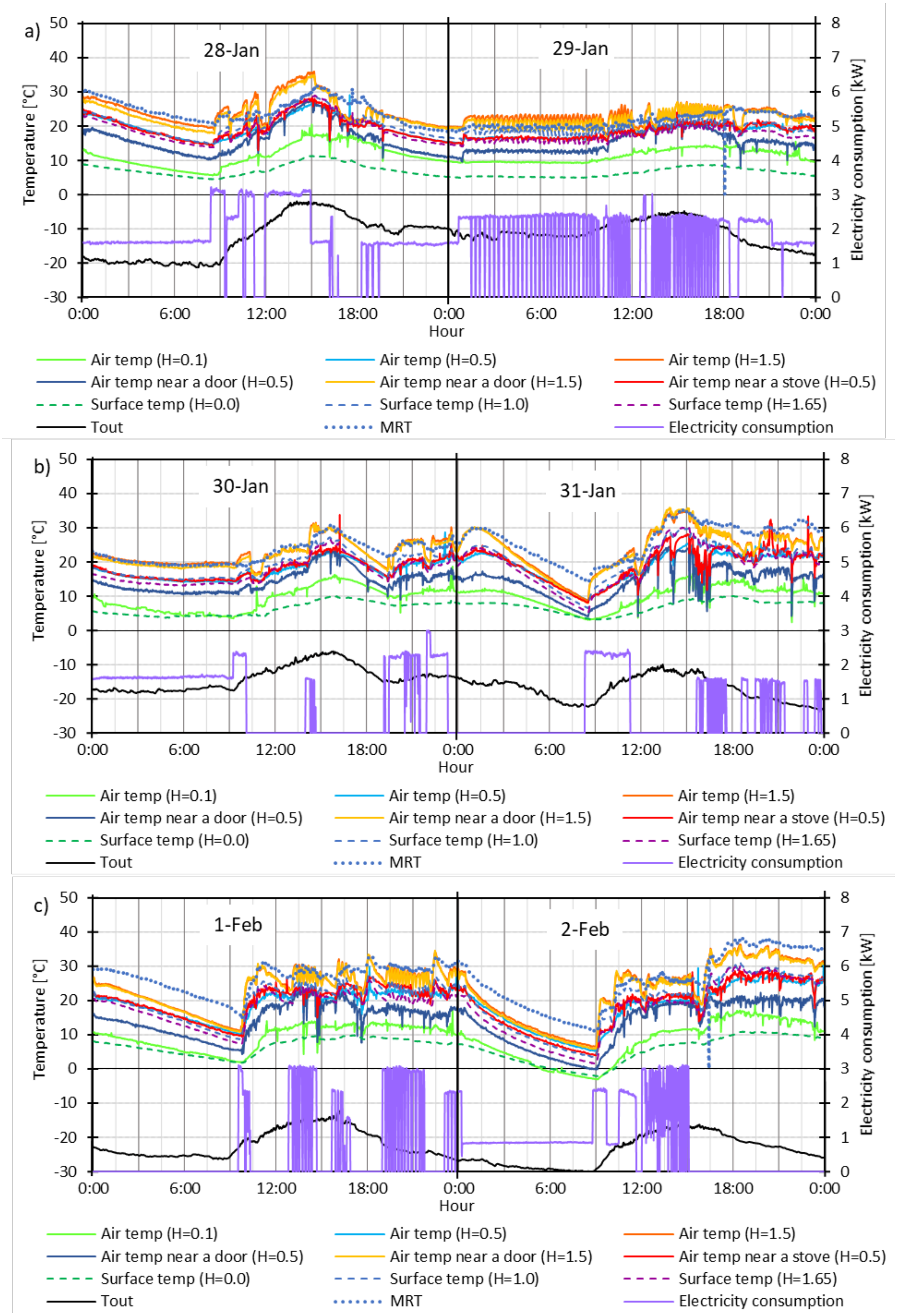


Fig. 4.16 Air and surface temperatures at various positions inside *Ger* A during Term II


a)
28-Jan
29-Jan
Temperature [°C]
Electricity consumption [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a door (H=0.5)
Air temp near a door (H=1.5)
Air temp near a stove (H=0.5)
Surface temp (H=0.0)
Surface temp (H=1.0)
Surface temp (H=1.65)
Tout
MRT
Electricity consumption
b)
30-Jan
31-Jan
Temperature [°C]
Electricity consumption [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a door (H=0.5)
Air temp near a door (H=1.5)
Air temp near a stove (H=0.5)
Surface temp (H=0.0)
Surface temp (H=1.0)
Surface temp (H=1.65)
Tout
MRT
Electricity consumption
c)
1-Feb
2-Feb
Temperature [°C]
Electricity consumption [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a door (H=0.5)
Air temp near a door (H=1.5)
Air temp near a stove (H=0.5)
Surface temp (H=0.0)
Surface temp (H=1.0)
Surface temp (H=1.65)
Tout
MRT
Electricity consumption

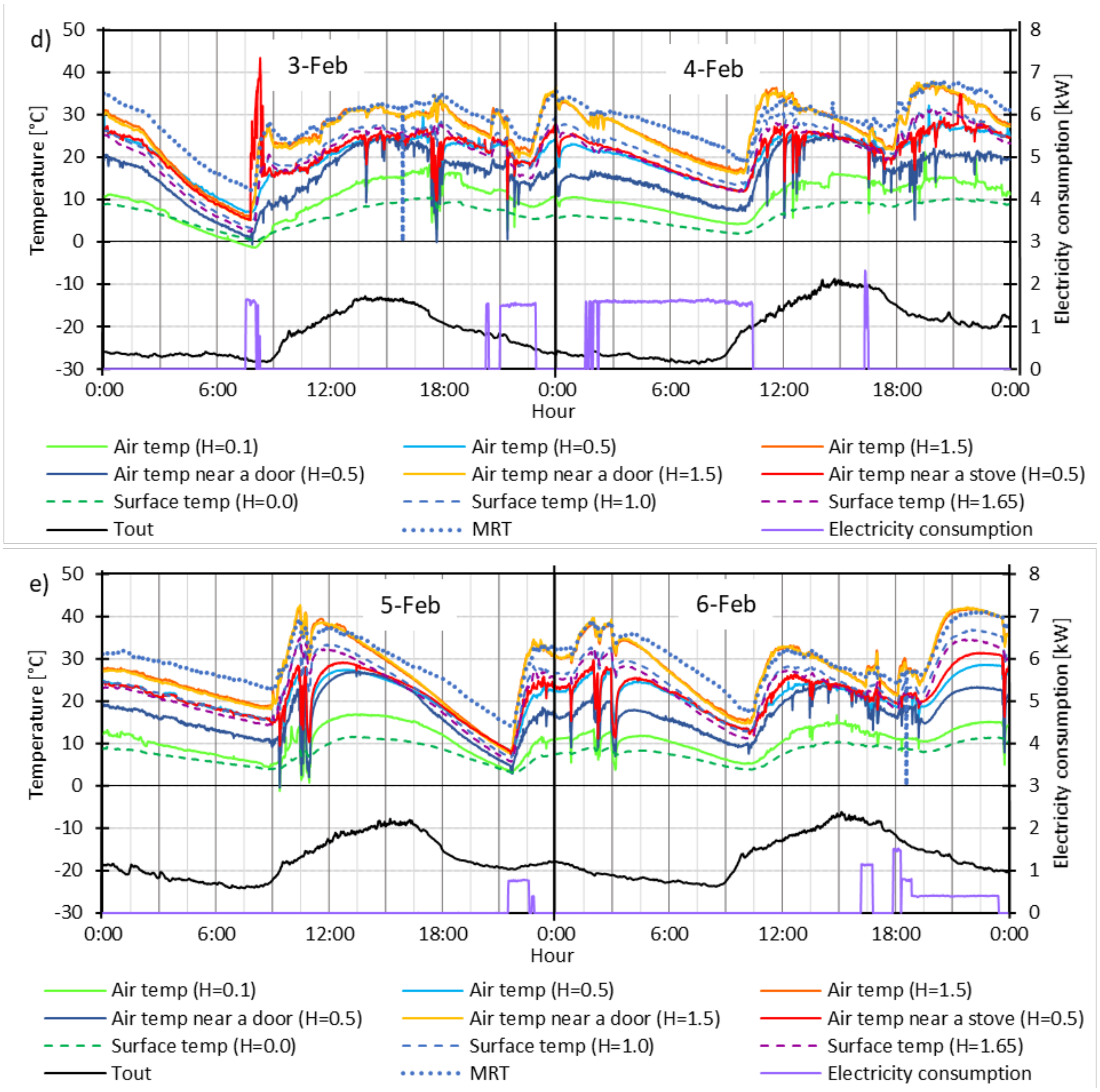
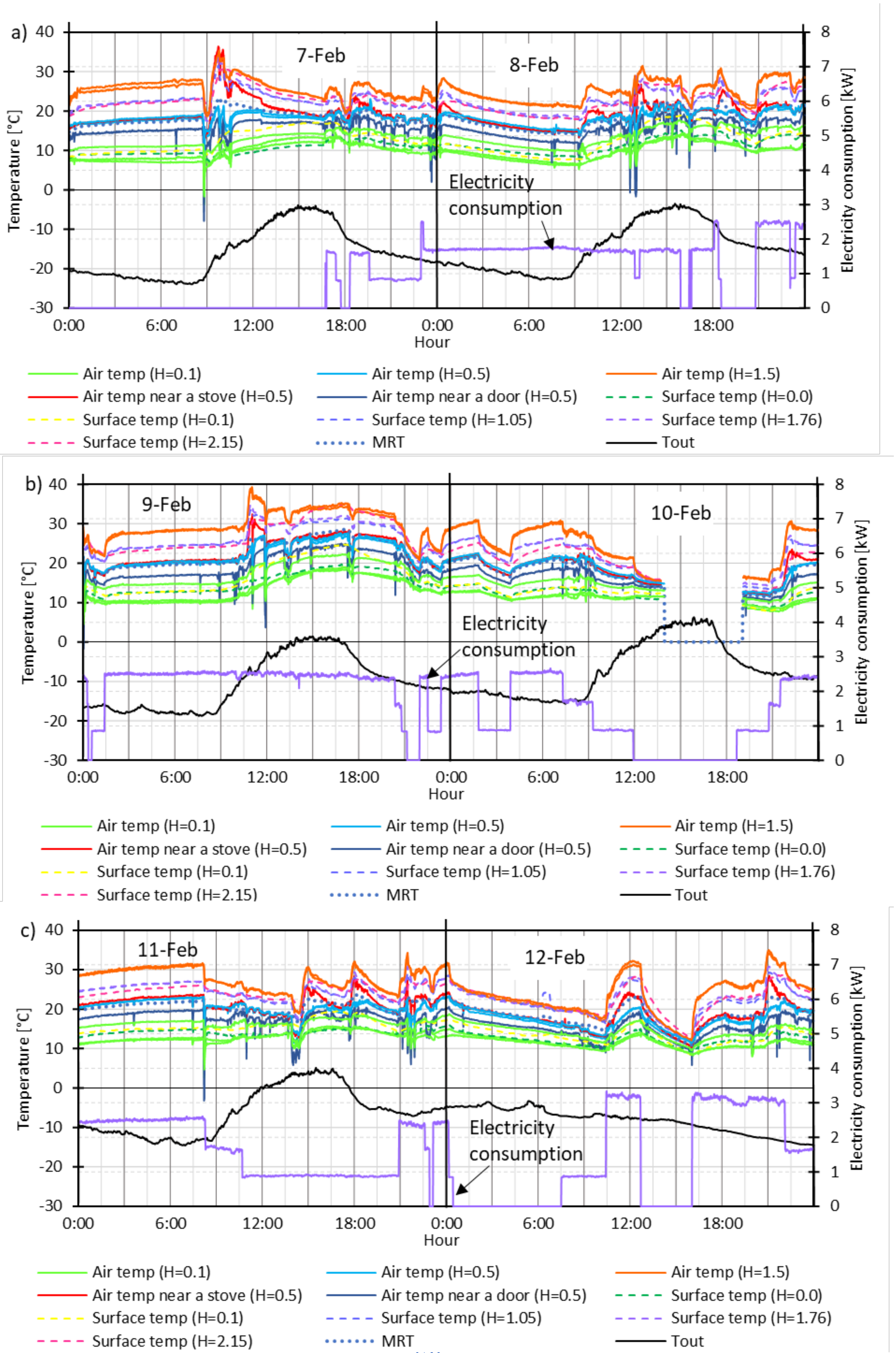


Fig. 4.17 Air and surface temperatures at various positions inside *Ger* B during Term II


a)
7-Feb
8-Feb
Electricity consumption
Temperature [°C]
Electricity consumption [kW]
Hour
b)
9-Feb
10-Feb
Electricity consumption
Temperature [°C]
Electricity consumption [kW]
Hour
c)
11-Feb
12-Feb
Electricity consumption
Temperature [°C]
Electricity consumption [kW]
Hour
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a stove (H=0.5)
Air temp near a door (H=0.5)
Surface temp (H=0.0)
Surface temp (H=0.1)
Surface temp (H=1.05)
Surface temp (H=1.76)
Surface temp (H=2.15)
MRT
Tout

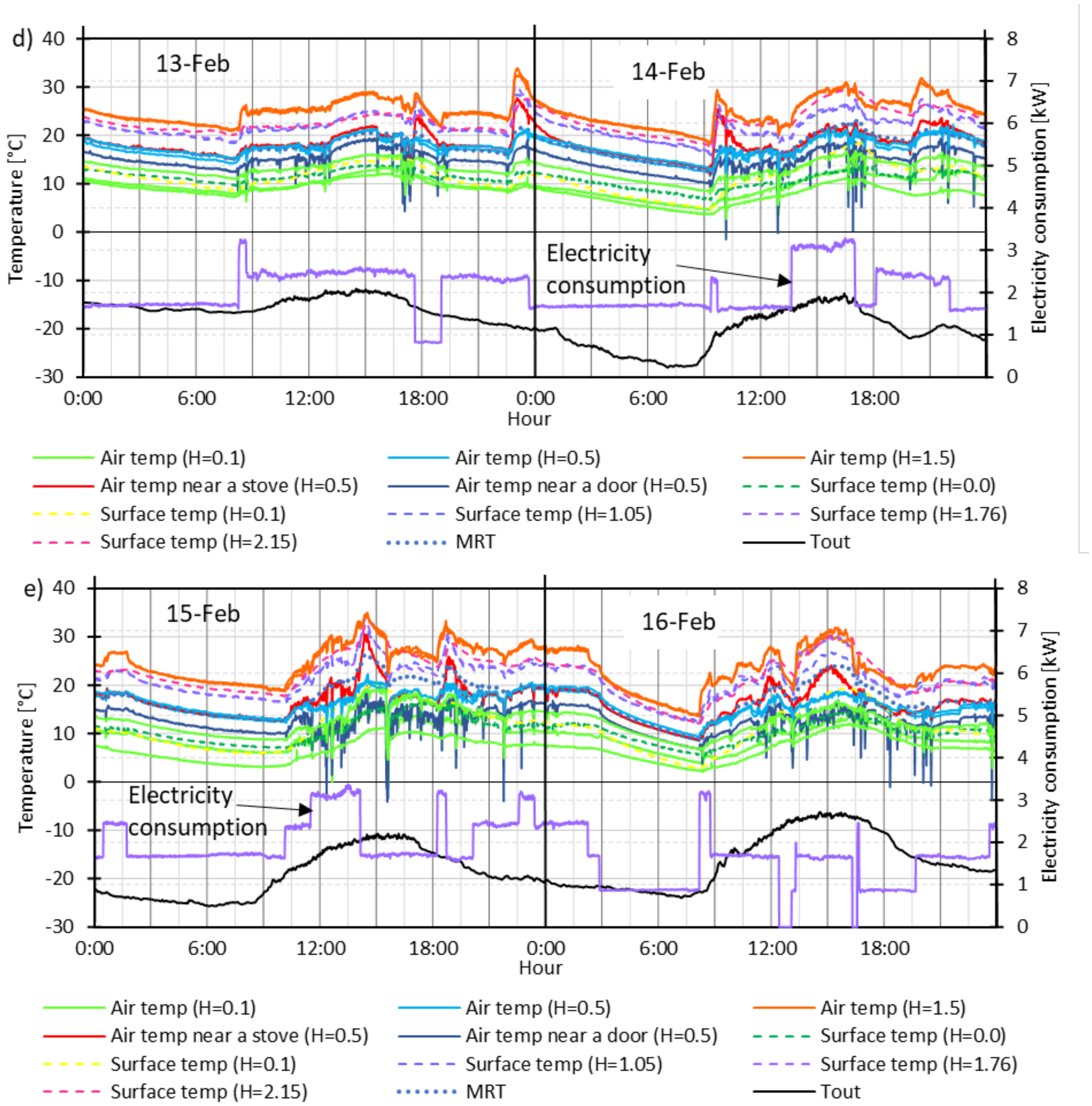
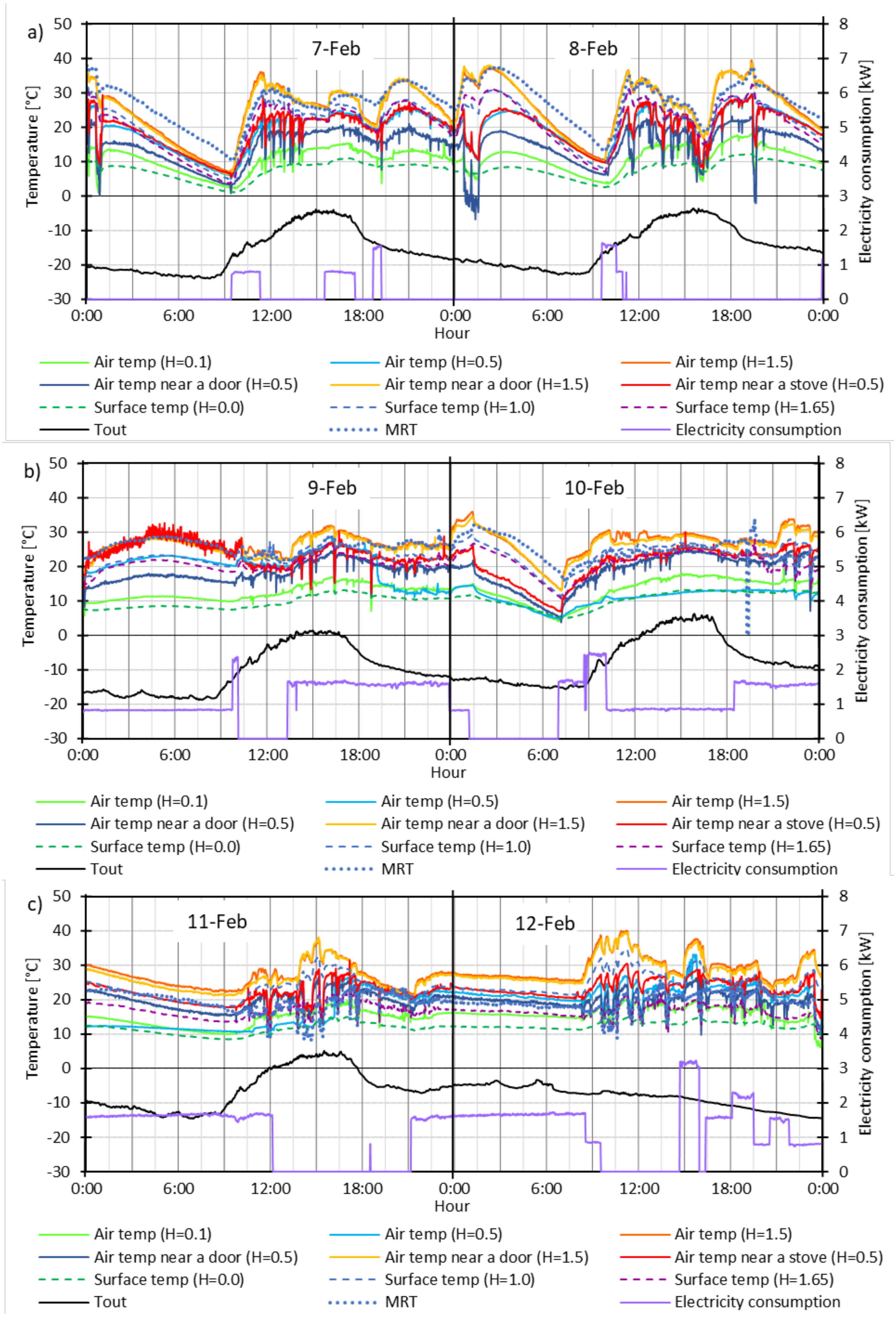


Fig. 4.18 Air and surface temperatures at various positions inside *Ger* A during Term III


a)
7-Feb
8-Feb
b)
9-Feb
10-Feb
c)
11-Feb
12-Feb
Temperature [°C]
Electricity consumption [kW]
Hour
0:00
6:00
12:00
18:00
Air temp (H=0.1)
Air temp (H=0.5)
Air temp (H=1.5)
Air temp near a door (H=0.5)
Air temp near a door (H=1.5)
Air temp near a stove (H=0.5)
Surface temp (H=0.0)
Surface temp (H=1.0)
Surface temp (H=1.65)
Tout
MRT
Electricity consumption

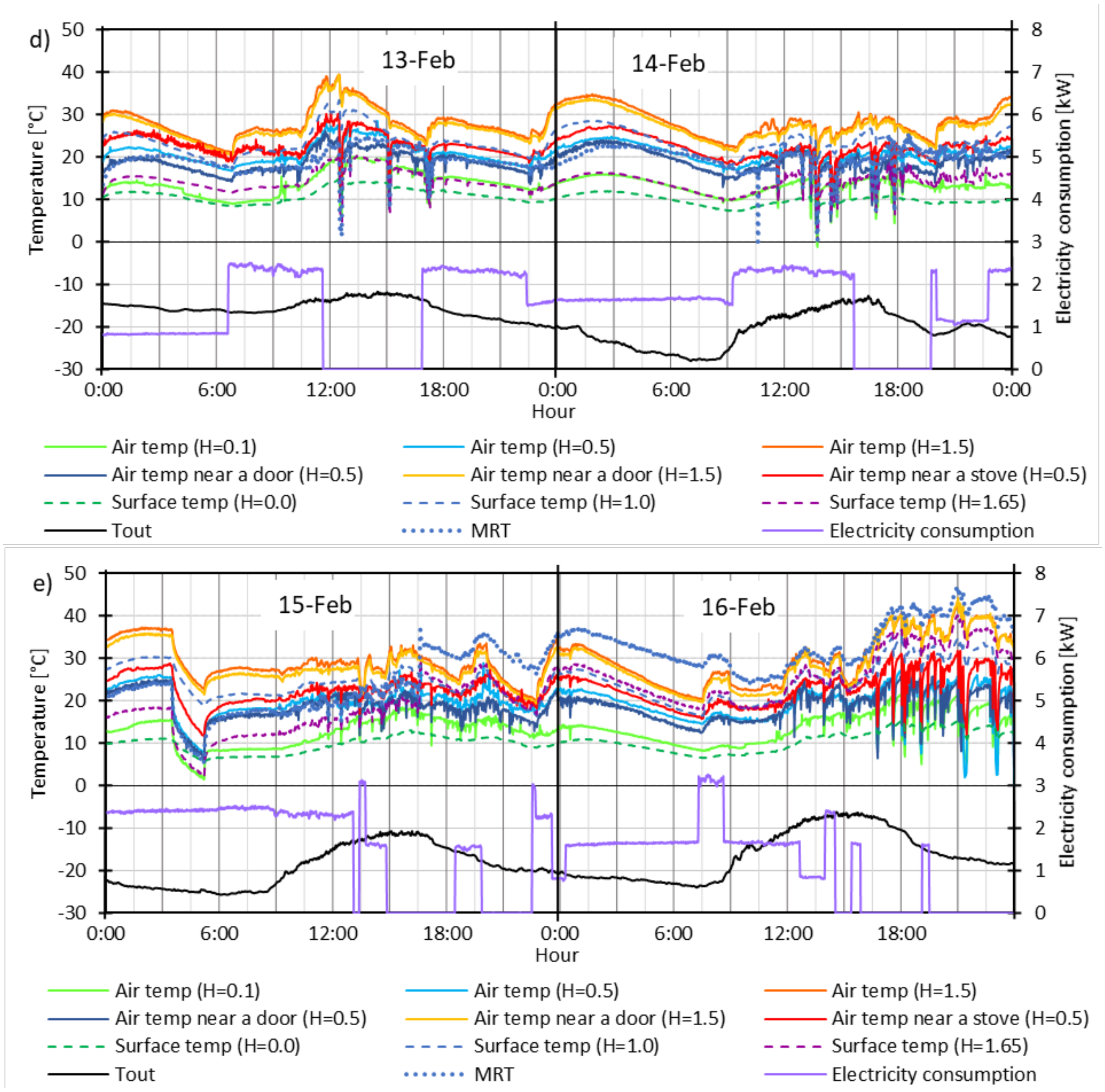


Fig. 4.19 Air and surface temperatures at various positions inside *Ger* B during Term III

4.3.4 Range of the indoor temperature under different outdoor air temperatures

The spatially averaged indoor air temperatures of *Gers* A and B against outdoor air temperature T_{out} and sol-air temperature T_{sol} are shown in Fig. 4.20, which are based on the 10 min average data. T_{sol} is determined by both the outdoor air temperature and the incident solar radiation, which is obtained as follows:

$$T_{sol} = T_{out} + \frac{a \cdot SR}{h}, \qquad (4.14),$$

where a is the solar absorptivity of the *ger* envelope, which is assumed to be 0.52; SR is global solar radiation [Wm^{-2}]; *h* is convection heat transfer coefficient of the external surfaces of the *gers*, assumed to be 10 W $m^{-2}K^{-1}$.

As shown in Fig. 4.19 (a), the indoor temperature of *Ger* A ranged from 2 to 32 °C because of heating, whereas the outdoor temperature ranged from –30 to 5 °C. During Term I, the indoor air temperature was not affected by the outdoor temperature owing to the strong radiation heating of the indoor air, whereas during Terms II and III, the indoor air temperature increased marginally during the daytime. A similar tendency is shown in the relation between T_{in} and T_{sol} in Fig. 4.19 (b). The indoor air temperature of *Ger* B ranged from 5 to 33 °C because of heating equipment used indoors, whereas the outdoor temperature ranged from –30 to 5 °C, as shown in Fig. 4.19 (c). The indoor air temperature of *Ger* B was not related to the outdoor and sol-air temperatures during all three measurement periods because of the strong heating of the indoor air. Conversely, when T_{out} was above –10 °C and T_{sol} was above 10 °C, the indoor temperature was at a relatively high level. However, considering that the periods of the day when the outdoor temperature or solar radiation was high generally coincided with the periods of day when the occupants were active and preferred to maintain the indoor temperature at a high value, the effect of the heating devices is expected to be more significant rather than outdoor conditions.

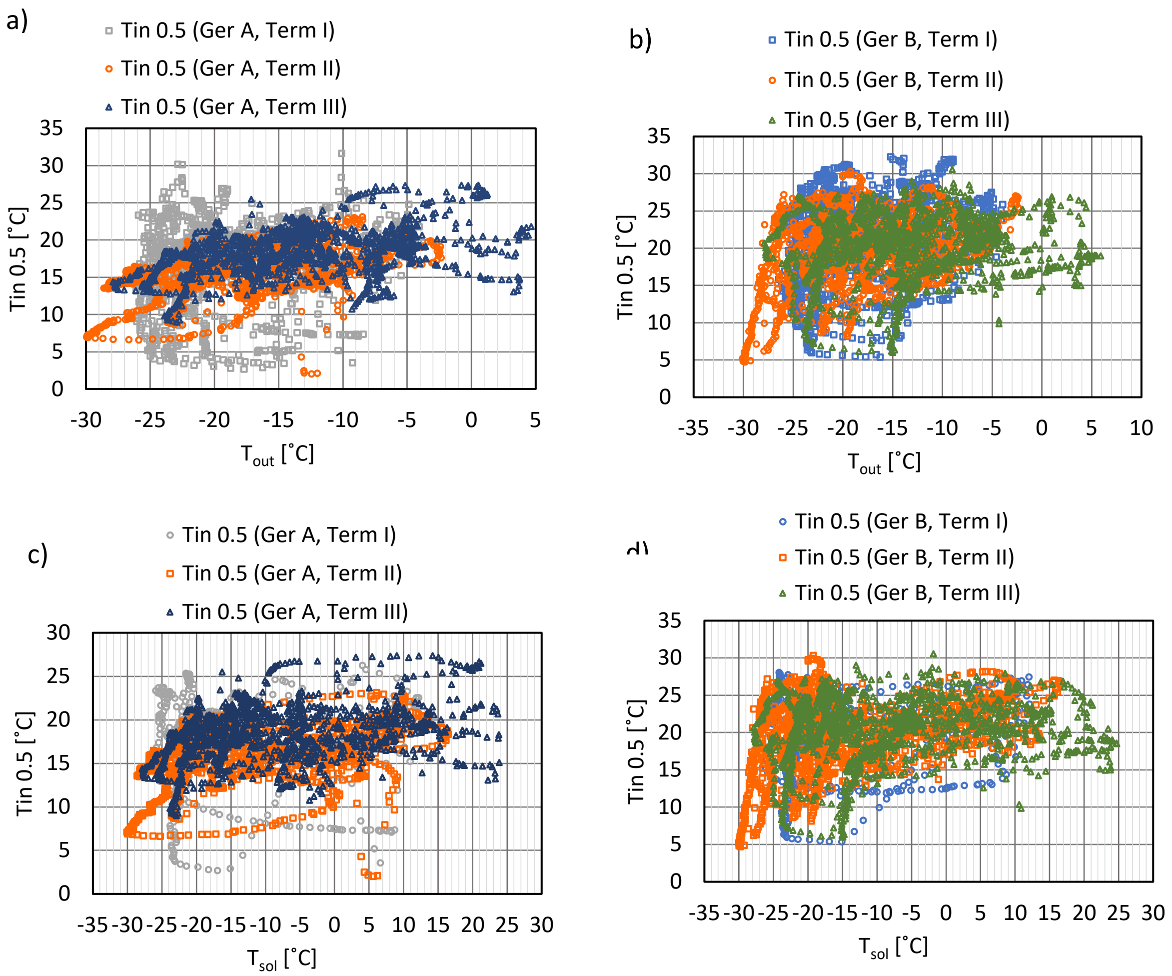


Fig. 4.20 (a) Scatter plot between the outdoor air temperature (T_{out}) and the indoor air temperature at a measurement height of 0.5 m ($T_{in-0.5}$) in *Ger* A; (b) Scatter plot between the sol-air temperature (T_{sol}) and the indoor air temperature at a measurement height of 0.5 m ($T_{in-0.5}$) in *Ger* A; (c) Scatter plot between the outdoor air temperature (T_{out}) and the indoor air temperature at a measurement height of 0.5 m ($T_{in-0.5}$) in *Ger* B; (d) Scatter plot between the sol-air temperature (T_{sol}) and the indoor air temperature at a measurement height of 0.5 m ($T_{in-0.5}$) in *Ger* B

4.3.5 Heating energy consumption

When *Gers* A and B were heated by a coal stove, the indoor air temperature started to increase, which is supposed to coincide with the timing of fire ignition, as mentioned previously. Therefore, the number of multiple local negative peaks of radiation energy can be considered as the number of fire ignitions accompanied by fuel addition. With this assumption, we estimated the number of fire ignitions per day (Table 4.5) for Term I. Although both the *gers* used stoves categorized as "improved stoves" having similar heating power, the result indicates a clear difference in the usage style of the occupants.

Table 4.5. Daily number of fire ignitions of the coal stoves during Term I

	***Ger* A**	***Ger* B**
Average	4.0	2.5
Standard deviation	1.2	0.8

Fig. 4.21 exhibits the daily average estimated radiation energy of the stoves used in *Gers* A and B during Term I and the daily average electricity consumption of the electric heaters during Term II in *Ger* A and the two days when *Ger* B was fully heated by the electric heater. Moreover, the estimated HDH is included for comparison. For the estimation of HDH, the author assumed an indoor setting temperature of 18 °C, which is the lower limit of an acceptable indoor air temperature in the Mongolian Standard (*Air quality MNS 4585 :2007*, 2007). The daily HDH was determined using the following equation:

$$HDH = \sum_{i=1}^{N} (T_t - T_i), \qquad (4.15)$$

where T_t is the base temperature, which is assumed to be 18 °C, and T_i is the average hourly temperature.

During Term I, the daily coal consumption was 25 kg per household, which is equivalent to 5.78 kW considering a calorific value of 20 MJ/kg, while the average estimated radiation heat of the stoves for the entire period was 5.08 and 4.23 kW for *Gers* A and B, respectively. Meanwhile, assuming that the stove surface and indoor air temperatures were 200 and 20 °C, respectively, we can estimate the convection heat between the stove and indoor air to be 1.49 and 1.83 kW for *Gers* A and B, respectively, considering a convection heat transfer coefficient of 6.9 W/m^{2}K, which is determined by the relation between the Nusselt, Grashof, and Prandtl numbers for the natural convection of a flat plate. This indicates that the average total heating power was 6.57 and 6.06 kW for *Gers* A and B, respectively, and the contribution of radiation to the total heating power of the stoves was approximately 77 and 70%, respectively. Although these values should be treated as approximations, the order is similar to both the calculated values based on the weight of coal used daily and the specifications provided by the manufacturers of the stoves (A: 6.5 kW and B: 7.5 kW).

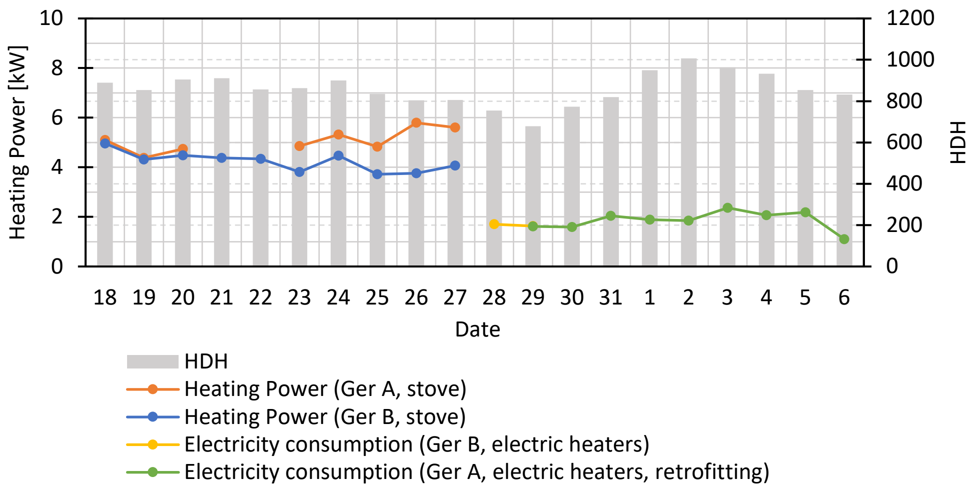


Fig. 4.21 Daily heating degree hours, estimated radiation heating power of stoves, and electricity consumption of heaters

In Term II, both the electric heaters and a coal stove were used at *Ger* B for most of the periods. Therefore, a fair comparison between the energy consumptions of the coal stove and electric heater can only be obtained from the data of *Ger* A. The electricity consumption during Term II at *Ger* A was approximately 1.8 kW, which was less than one-half of the estimated radiation heat, one-third of the heating power calculated from coal use, and the values mentioned in the specifications of the manufacturers. In contrast, the HDH ranged from 800 to 950 during Term I and decreased by ~17% on January 28 and 29. From the middle of Term II, the HDH range increased by ~30% when compared to the beginning of Term II; however, the electricity consumption of *Ger* A increased by only 10%. Furthermore, the fact that *Ger* B had to predominantly use both electric heaters and a coal stove to maintain the acceptable indoor temperature during Term II indirectly indicates the effect of the retrofitting of *Ger* A. Although the HDH range in Term II was higher than that in Term I, the energy consumption in Term II was three times lower than the calculated heating power in Term I. This indicates that the coal stove consumes more energy than the electric heater. This excess energy consumption is partly caused by the primitive function of the stoves to module the intensity of the coal combustion according to the indoor thermal conditions.

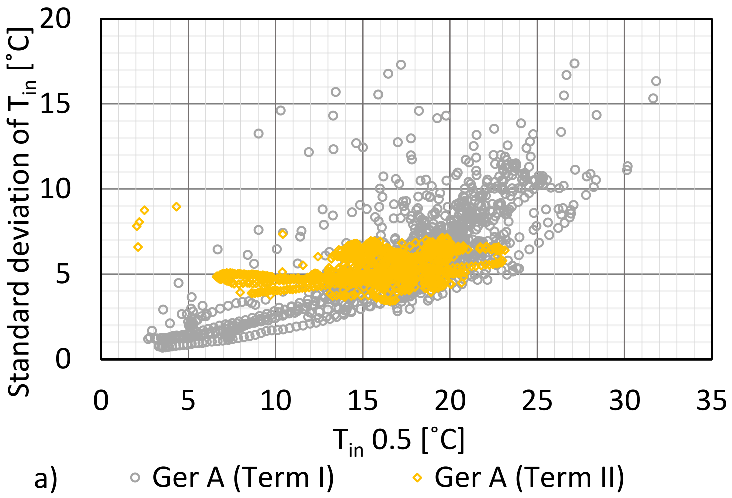
4.3.6 Spatial heterogeneity of indoor air temperature

The relation between the spatially averaged indoor air temperature at a height of 0.5 m (hereafter, $T_{in\text{-}0.5}$) and the standard deviation of the indoor air temperature at all the measurement positions for Terms I and II in *Ger* A and Term I and two days of Term II with electric heaters in *Ger* B are shown in Fig. 4.22. During Term I, the spatial nonuniformity of the indoor air temperature increased with the increase in $T_{in\text{-}0.5}$ and the standard deviation decreased with the decrease in $T_{in\text{-}0.5}$ caused by extinguishing the fire in the stoves in both *Gers* A and B.

Fig. 4.23 shows the relation of the spatially averaged indoor air temperature at a height of 0.5 m with the values at 0.1 and 1.5 m during Term I in *Gers* A and B and Term II in *Ger* A. To reduce the influence of the rapid temperature drops due to the short-duration door opening actions, 10 min averaged values were used for these graphs.

Fig. 4.23 shows that the temperature differences between the levels of 0.1 and 1.5 m were ~12 and 18 °C during Term I with stove heating under the conditions of $T_{in\text{-}0.5}$ = 20 and 30 °C, respectively. Conversely, ASHRAE 55 (2017) indicates that the vertical air temperature difference between the head and ankle levels should not exceed 3 °C for seated occupants and 4 °C for standing occupants for achieving a condition of thermal comfort. Although recent studies, such as Mohlenkamp et al. (2019), reported that the acceptable vertical temperature gradient for the thermal comfort of occupants might be considerably larger than specification in this comfort standard, the strong thermal stratification of the indoor space of *gers* is completely different from the fully air-conditioned environment of modern buildings with relatively uniform temperature distribution.

When comparing the data of Terms I and II, it can be noted that the stratification of the indoor air temperature tended to be small when ceramic heaters were used and the *ger* retrofitted to improve the insulation. Particularly, the temperature difference between the 1.5 and 0.1 m levels during Term II was significantly smaller than that for Term I with stove heating. A potential reason for this contrast between the heating devices is the large infiltration rate at the interface between the floor and the *ger* envelopes that is caused by the stack effect created by the conventional stoves with significantly higher surface temperature, which is generated by the combustion of coal, when compared to the ceramic heaters. This implies that coal stoves may cause larger heat loss owing to the buoyancy-induced infiltration when compared to the convection-type electric heaters, although these heating devices can generate similar levels of mean indoor air temperature.



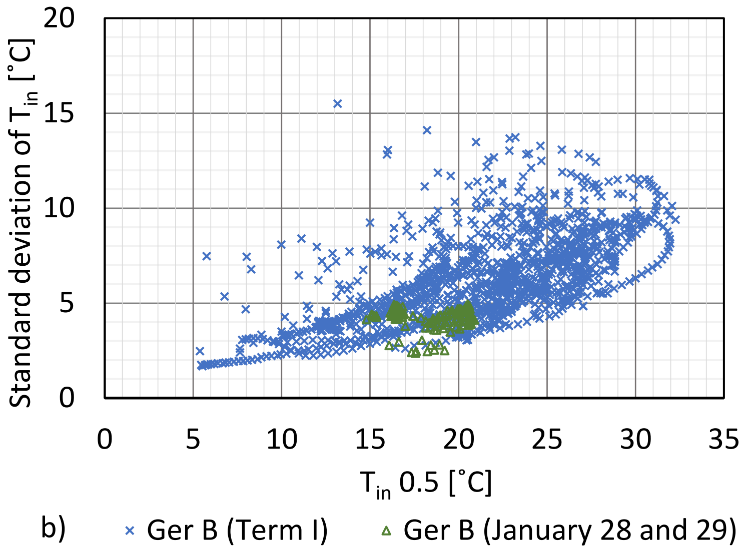


Fig. 4.22 Relation between the spatial average air temperature at a height of 0.5 m and the standard deviation of the indoor air temperature for all the measurement positions in (a) *Ger* A and (b) *Ger* B

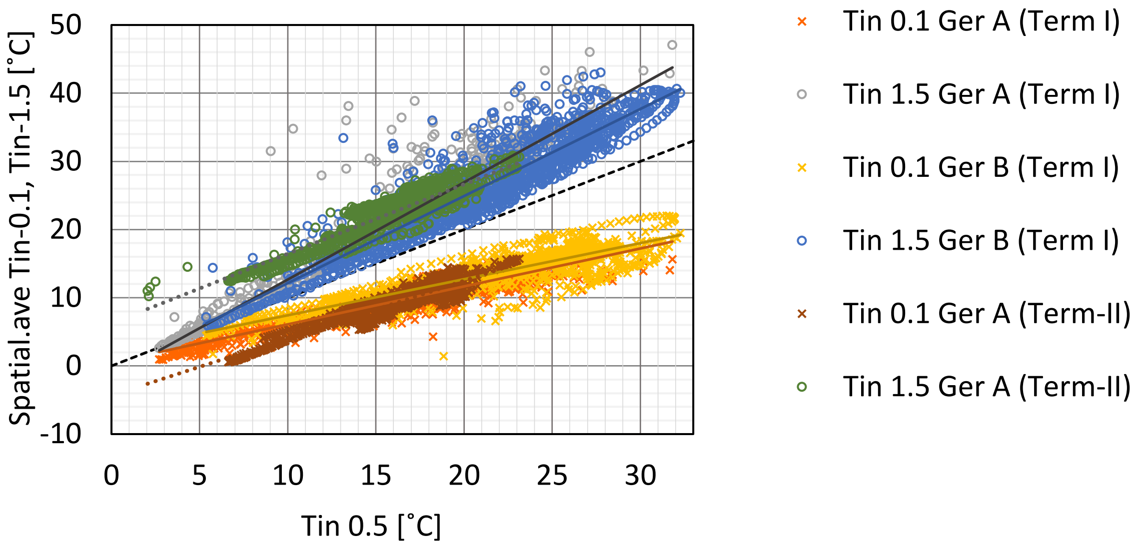


Fig. 4.23 Relation between the spatial average air temperature at a height of 0.5 m and at different heights from the floor level (0.1 and 1.5 m)

4.3.7 Surface temperature of baseline *ger* envelopes and floor

The relations between the indoor air temperature ($T_{in\text{-}0.5}$) and surface temperatures at various positions on the *ger* envelope and floor of the baseline *Gers* A and B during Term I when the air was heated by a coal stove is shown in Fig. 4.24. Similar to the relation of air temperature at different heights, as shown in Fig. 4.23, the surface temperature with respect to changes in $T_{in\text{-}0.5}$ was higher at higher positions of surface temperature measurement. Particularly, the roof surface temperature of *Ger* A at a height of 2.15 m sometimes exceeded 50 °C. When considering the small thermal resistance of the envelopes and cold outdoor air temperature that was below –10 °C, this trend is assumed to be caused by a hot updraft above the stove owing to the natural convection and direct radiation energy emitted from the stove.

The temperature of the floor and wall surface at 0.1 m was reduced by ~25 °C. This reduction in temperature was caused by the stratified indoor air temperature and cold inflow through the lower part of the *ger* envelopes owing to the stack effect. It should be noted that the sensor for measuring the floor surface temperature was positioned near the wall and relatively far from the stoves to minimize the disturbance to the daily life of the occupants. Therefore, the sensors located on the floor were not directly heated by the radiation generated from the stoves.

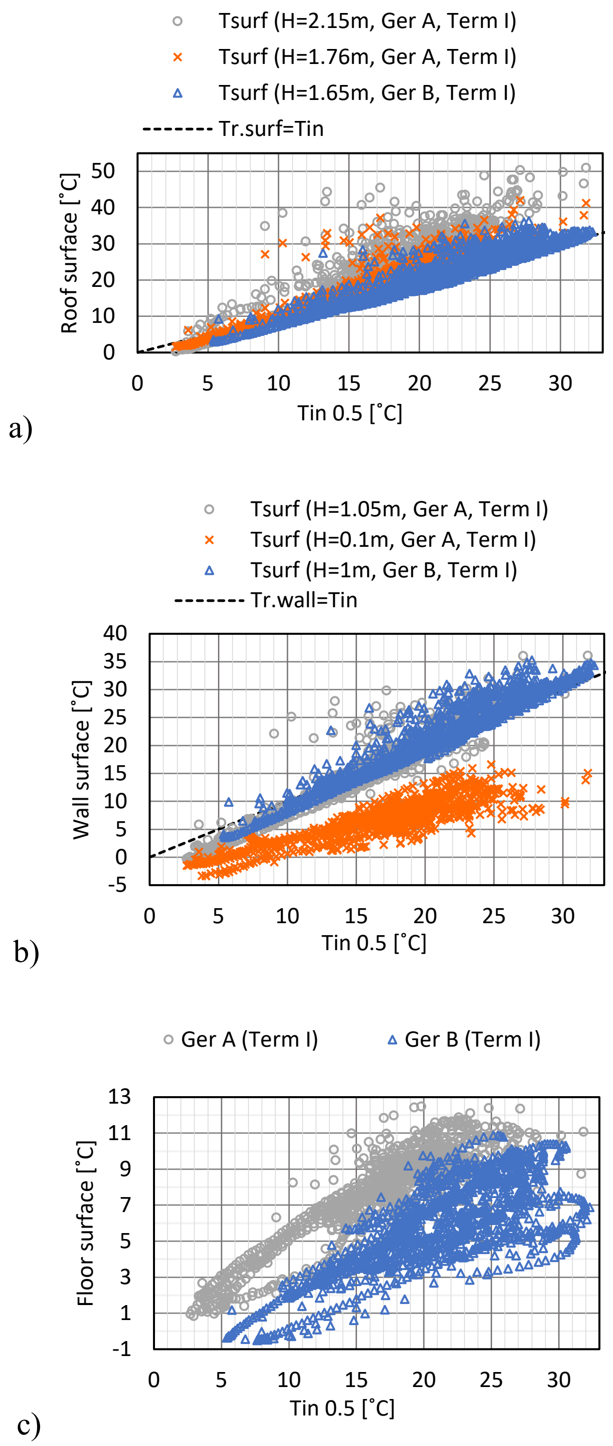


Fig. 4.24 Relation between the spatial average air temperature at a height of 0.5 m and (a) roof surface temperature, (b) wall surface temperature, and (c) floor surface temperature

4.3.8 Surface temperature of *ger* envelopes and floor of retrofitted *ger*

Fig. 4.25 shows the temporal variations in the surface temperatures of the *ger* envelope of the baseline *Ger* A when it is first heated using a coal stove and when it is heated using an electric heater after retrofitting the *ger* with the insulation prototype. Generally, the temporal variation in the temperature of each part shows a similar pattern as that of the air temperature in the room, and the effect of the heating device is assumed to be dominant.

During the baseline condition, the wall temperature was lower than the roof temperature; in contrast, after being retrofitted with the insulation prototype, the wall and roof temperatures become almost identical. However, the floor temperature was low, ranging between 0 and 15 °C during both periods. This is probably because of the strong thermal stratification of indoor air and the poor insulation performance of the floor slab consisting of only wooden boards. In *Ger* A, the occupants usually wore boots or woolen indoor shoes, probably to avoid the cold sensation caused by the low temperature of both the floor surface and the cold air near the floor.

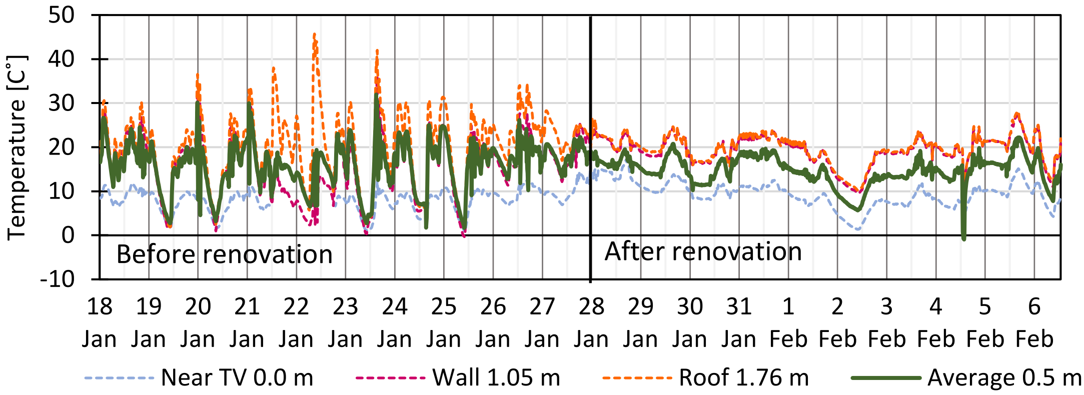


Fig. 4.25 Variation in surface temperature at various heights before and after retrofitting

4.3.9 Thermal exposure of occupants at baseline *gers* (Term I)

Fig. 4.26 shows the temporal variations in the calculated MRT and spatially averaged air temperature at a height of 0.5 m ($T_{in\text{-}0.5}$) on January 18 and 26 during Term I, in which both the *gers* were heated using a coal stove and were occupied by at least one resident to assess the thermal exposure of the occupants. The MRT values are always higher by 5–15 °C than the indoor air temperature. The temporal patterns of the MRT of the *gers* are similar to those of air temperature, except for the time period when the temperature decreased owing to the opening of the door. MRT was always sustained at >20 °C, even though $T_{in-0.5}$ had decreased below 10 °C in the early morning just before the addition of coal to the stove.

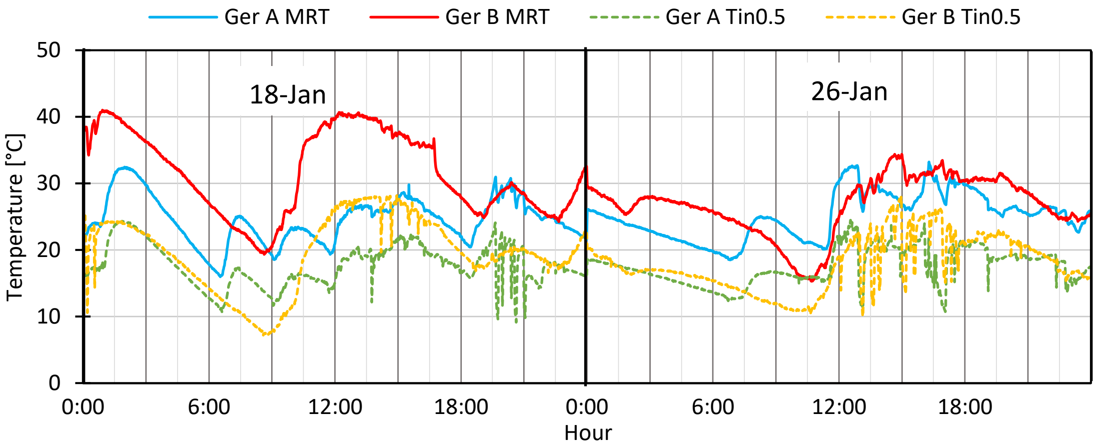
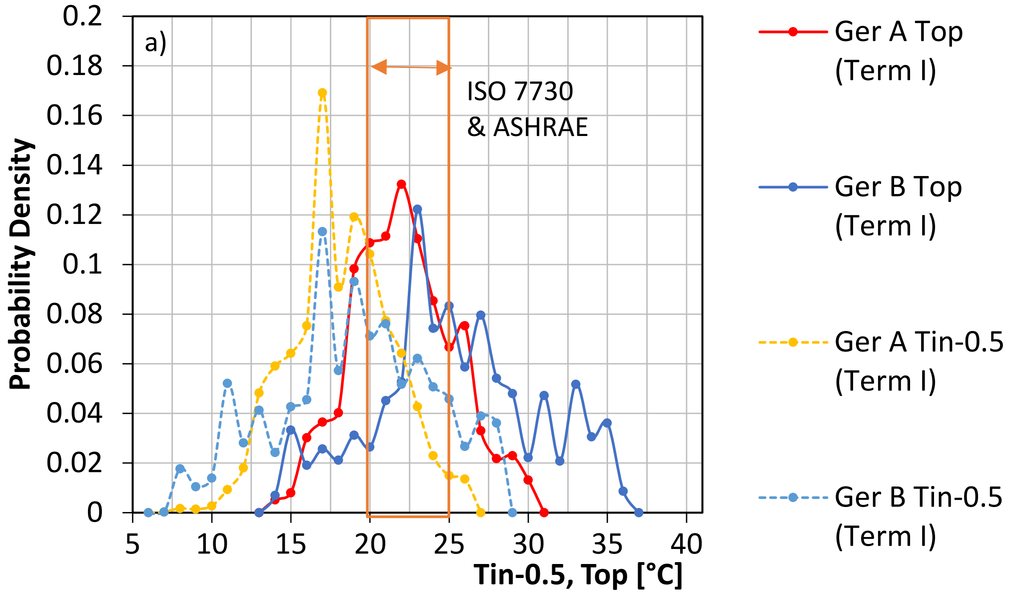


Fig. 4.26 Temporal variation in mean radiant and indoor air temperatures during the two fully occupied days in Term I

Fig. 4.27 illustrates the probability density distributions and cumulative probability distributions (CPDs) of $T_{in-0.5}$ and the operative temperature, T_{op}, on January 18 and 26. $T_{in-0.5}$ of *Ger* A ranged from 6 to 29 °C, and was less than 18 °C over half the staying hours despite the large energy consumption for heating that is shown in Fig. 7. In contrast, the air temperature of *Ger* B was marginally higher than that of *Ger* A. The value for a CPD of 50% was 22 °C. When compared to the indoor air temperature, T_{op} of the *gers* ranged from 13 to 37 °C, suggesting effective radiative heating of the stove for occupants, even though the indoor air temperature was sometimes lower than standard recommend temperature for a modern building. In BS ISO 7730 (2005), the winter comfort criterion in dwellings ranges from 20 to 24 °C (*BS EN ISO 7730 : 2005 Ergonomics of The Thermal Environment*, 2005), and the comfort range according to ASHRAE 55-(2017) is 19.5–24.5 °C. When compared with these standards, the CPDs in Fig. 4.22 (b) reveal that, for *Ger*s A and B, the temperatures at 74 and 85% of the day were above the lower limit of the comfort range, respectively. Furthermore, the operative temperatures at 50% of the time in *Ger* B and 20% of the time of *Ger* A were higher than the upper limit in the comfort range.



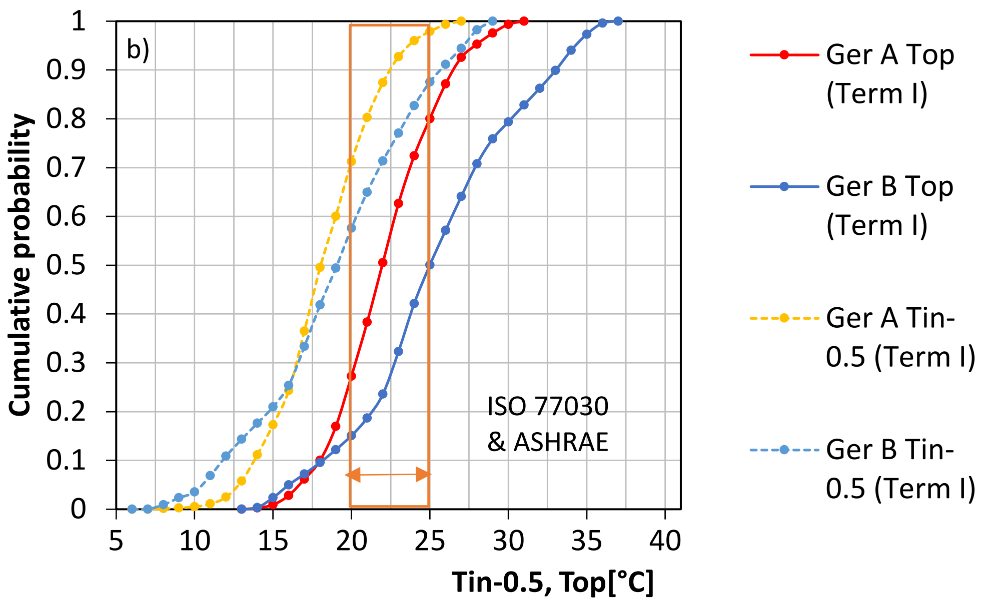


Fig. 4.27 (a) Probability density distributions and (b) cumulative probability distributions of the operative temperature (T_{op}) and spatially averaged air temperature at a height of 0.5 m ($T_{in-0.5}$)

4.3.10 Operative temperature of the retrofitted *ger* with electric heaters

The temporal variations in the operative and indoor air temperatures of *Ger* A during four days of Term I (baseline *ger* + coal stove) and 10 days of Term II (retrofitted ger + electric heating) are shown in Fig. 4.28. Before the retrofitting, the operative temperature predominantly ranged between 15 and 30 °C, except for approximately 6 h on January 24 and 25. Moreover, the operative temperature was higher than the air temperature by up to 5 °C during the peak durations, suggesting strong radiation heating of the stove.

In contrast, during Term II, the operative temperature was almost equal to room temperature. This is because T_r was almost equal to $T_{in\text{-}0.5}$ despite the usage of convection-type electric heaters. This is due to the long-wave radiation emitted from the surface of the insulation panels, which was always approximately 5 °C higher than $T_{in\text{-}0.5}$, and from the floor surface, which was always approximately 5 to 8 °C lower than $T_{in\text{-}0.5}$. When the operative temperature after the renovation and during the time when the occupants were at their *ger*, the results primarily showed a range of 15 to 20 °C. As the lower limit of the ASHRAE comfort range is approximately 17.5 °C, the indoor thermal condition during this demonstration test was unfortunately not satisfactory for the occupants. One of the reasons for this result is that the power of the electric heaters used in the demonstration test could not be sufficiently increased. Owing to the age of the old power distribution system in the *ger* district, the electric heaters could not be operated at maximum power because of the risk of leakage and fire. Nevertheless, if the floor had been also insulated during Term II, the floor surface temperature could have been higher than the observed data, increasing T_{op} despite the limited electric heating power.

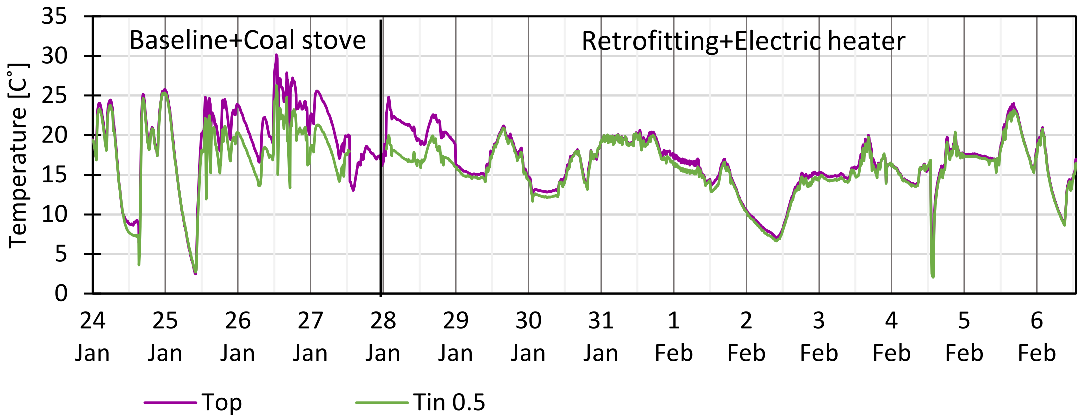


Fig. 4.28 Temporal variation in the operative temperature (T_{op}) and indoor air temperature at a height of 0.5 m ($T_{in-0.5}$). The *ger* was occupied by at least one resident throughout the day on January 26 and February 3 and 5

4.4. Conclusions

Field measurements were conducted in two urban *gers* in Ulaanbaatar, Mongolia to understand the thermal features of traditional *gers* that are heated by a fuel stove under the usual behaviors of occupants in winter. Moreover, the demonstration tests of insulation-related retrofitting and the windbreak room was conducted under the condition where electric heaters were used. The findings of this field measurement are summarized below.

- Daily variations in indoor air temperatures of *gers* varied by household and day and were strongly affected by variations in the heating power of stoves, which is influenced by the timing and amount of coal added to the stove by the occupants.
- Under the conditions of intense stove heating, the vertical difference in indoor air temperature was large. The air temperature at a height of 1.5 m near the ceiling sometimes exceeded 40 °C, while the air temperature near the floor was always less than 20 °C. This stratified temperature field was more intense when a coal stove was used when compared to the field when convection-type electric heaters were used.
- Consequently, the operative temperatures in *Gers* A and B were above the lower limit of the comfort range specified in the ASHRAE standard for 74 and 85% of the overall time, respectively. Conversely, overheating occasionally occurred in *Gers* A and B, resulting in operative temperatures above the upper limit of the comfort range for 50 and 20% of the overall time, respectively, owing to the limited functionality of the stove

in modulating the heating power. Moreover, the occupants sometimes deliberately opened the door to let in cold air from outside, which was observed as a countermeasure to overheating.

- The operative temperature of the retrofitted *ger* was identical to the indoor air temperature as the stove was not used after the *ger* was retrofitted.

To secure the mobility of a *ger*, thick, stiff, and well-insulated envelopes such as those installed in typical buildings in Northern Europe have never been adopted despite the cold climate in Mongolia. Instead, people in Mongolia have always preferred stoves with strong radiation heating devices placed at the center of the circular plane in the *gers*, since the inception of nomadic society till today, where urban *ger* districts have developed. The current field measurements illustrate the unique characteristics of the indoor thermal condition of baseline urban *gers* and demonstration tests conducted on the retrofitted *ger* that are heated by electric heaters. Although the examined *gers* are traditional dwellings that are indigenous to Mongolia, similar traditional mobile dwelling exists or traditionally existed in certain Central Asian countries and East European countries. The result of this measurement also provides significant insights into the physical environmental factors behind the design of such nomadic traditional settlements.

The effectiveness of direct radiant heating using primitive fuel stoves and the instability of their thermal output should also be emphasized. In modern buildings, fuel stoves are rarely used, and when using a building energy simulation (BES) to estimate the heating load—and to assess the indoor thermal comfort level—the room temperature is usually assumed to be maintained at a given temperature. Conversely, the results of this study suggest that stoves used *gers* have a limited degree of control, which lead to large temporal variations in room temperature, sometimes resulting in air temperature below the comfort range. Although the room air temperature becomes lower than the comfort range, direct radiant heating from a stove can maintain the thermal comfort of the occupants. These facts suggest that the BES—which does not consider characteristics such as direct radiant heating, which is quite different from modern air-conditioned buildings—may not adequately reflect the actual situation. The findings of this study could also be valuable for exploring the indoor thermal environment of various buildings heated by a primitive stove in a wide range of regions.

Energy consumption of the retrofitted *ger* could not be directly compared to the baseline *ger* owing to the differences in the heating devices. However, the estimated heating power of the coal stove was three times higher than the heating power of the electric heaters, suggesting excessive energy use by the coal stoves. Although the satisfaction of the occupants toward retrofitting was positive, this positive evaluation was primarily based on the bright-colored interior appearance. The demonstration test of retrofitting indicates that further improvement for the floor insulation is required.

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Chapter 5
Conclusions and Future work

5.1 Conclusions

Globally, three billion people lack access to clean and modern energy, primarily in developing countries, resulting in 4.3 million premature deaths each year. Ulaanbaatar is the capital city of Mongolia, where the winter temperature drops to −40 °C in winter and 58% of the households rely on primitive coal stoves for space heating. Such a high fraction of coal stove usage is due to the presence of *ger* districts, which are unplanned residential districts with limited urban infrastructure. In a *ger* district, half the occupants live in *gers*, which are traditional nomadic housing composed of a thin wooden structure covered by a few layers of felt sheet, whereas the remaining half of the occupants live in *baishins*, which are self-built detached houses. The current energy production of Mongolia is insufficient for heating the poorly insulated *gers* and *baishins*; consequently, implementing a switch from coal stove usage to a clean heating system is challenging. Therefore, to reduce the energy consumption, the insulation system of *gers* and *baishins* must be improved. However, the *ger* is a portable tent, where the application of the insulation system of a modern building is difficult. Therefore, in this thesis, an affordable and tailored insulation system for the *ger* is developed. To develop affordable and tailored insulation systems for *gers*, several consecutive studies were conducted, i.e., field survey and observation, development of insulation prototype, indoor thermal measurement of the urban *gers* in Ulaanbaatar, Mongolia, and demonstrations of the developed insulation system.

Chapter 1 discussed the background of the research and reviews previous research. The objective of the research were presented in this chapter.

Chapter 2 discussed a field survey that was conducted on 49 *gers* in Ulaanbaatar, Mongolia to understand the current living condition of urban *gers* and presented its findings. The survey investigated the design of the *ger*, materials, age of the *ger*, living style of the occupants, behavior related to energy use, perception toward indoor thermal condition during winter, and contentment with their living environment. The result of the survey indicates that the *ger* is affordable for low-income households because of the well-standardized design of *gers* and the local availability of materials. Despite its low cost, the *ger* can provide a relatively comfortable environment. Occupants of the *ger* have less knowledge about the quality and performance of *ger* felt sheet envelopes. The national standard recommends that felt sheets should be replaced every five years; however, in reality, occupants do not replace felt sheet unless it is completely degraded.

Chapter 3 presented the development of a retrofitting method for improving the thermal environment of the g*er* at a moderate cost. The methods included the installation of insulation panels on the roof and wall and the attachment of a windbreak room in front of the door. The proposed design aims for affordability by using locally available materials and a simplified manufacturing process. Occupants can install insulation panels by themselves, which considers their habit of dismantling and reassembling *gers* at least once a year. The thermal transmittance of the *ger* envelope improved from 7.5 to 2.2 $Wm^{-2}K^{-1}$.

In Chapter 4, the thermal environment of two urban *gers* of typical size and materials that were heated using coal stoves, which were located in Ulaanbaatar, Mongolia, was investigated. Measurements was continuously obtained for 30 days in three stages. During the first 10 days, measurements were obtained under baseline conditions, i.e., the two *gers* were heated using a coal stove. During the second period of 10 days, one *ger* was insulated with the developed insulation system, which was discussed in Chapter 3, and the heating device was replaced by an electric heater. In the final 10 days, a windbreak room was attached in front of the door in both *gers* and an electric heater was used in both *gers* along with a coal stove. The indoor thermal variables were observed while the occupants continued with their normal behavior. In the baseline stage, the indoor air temperature of the *ger* was strongly affected by the heating power of the stove and daily variations in the indoor air temperature depended on the timing of fire ignition and amount of coal that was added to the stove. Owing to severe heating effect of the stove, the heating temperature stratification of the indoor air temperature was large when the stove was used. The temperature at the measurement position near the floor was always less than 20 °C, whereas that at the measurement position at a height of 1.5 m sometimes exceeded 40 °C. Because of the stove, the radiation effect MRT was always maintained above 20 °C, despite the indoor air temperature dropping below 10 °C at certain times. The operative temperature was above the lower acceptable range stipulated in the ASHRAE comfort range for 74 and 85% of the overall time in *Gers* A and B, respectively. However, occasional overheating occurred 50 and 20% of overall time in *Gers* A and B, respectively, owing to the limited functionality of the stove in terms of adjusting the heating power. Therefore, occupants modulated the indoor air temperature by opening doors to allow the external cold air. *Ger* residents in Mongolia rely on the strong radiation of a stove that is placed at the center of the *ger*, instead of well-insulated envelopes. The measurement results of the first 10 days explained how Mongolian nomads managed to create a comfortable environment in cold winters. Although *gers* are primarily used by Mongolians, similar nomadic circular housing existed in some Eastern European and Central Asian countries.

The effectiveness of direct radiant heating using the primitive coal stoves and the fluctuations in the temperature were also discussed. Even in a room with air temperature below the comfort range, which is due to direct radiant heating, the occupants can maintain their thermal comfort.

During the demonstration of the insulation-related retrofitting, owing to the poor electricity supply maintenance, the electric heating device was unable to generate its maximum output; however, the thermal perception of occupants regarding the retrofitting for improved insulation was generally positive. The average indoor air temperature was approximately 15 °C; however, the floor temperature was low; consequently, in the future, floor insulation-related retrofitting may also be required.

The findings of this study are important to determine the indoor thermal environment of housing units heated by fuel stoves. In a near-future scenario, it is important to replace coal stoves with an electrically powered heater to reduce air pollution, save excessive energy consumption, and prevent health risks related to indoor air quality.

5.2 Future work

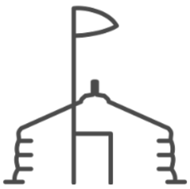
This study contributed to the strategy building to improve the indoor thermal condition and indoor air quality of urban *gers* located in Ulaanbaatar, Mongolia. Future recommendations are summarized below:

1) The proposed retrofitting method for the walls and roof can remedy the indoor temperature stratification; however, the demonstration of the thermal measurements in the retrofitted *ger* has revealed the stratified temperature in the floor area; consequently, floor insulation-based retrofitting must be developed to fully improve the indoor thermal stratification.
2) The usage of fuel stoves produces a high level of household air pollution with health-damaging pollutant particles that are inhaled to the lungs. Long-term indoor pollutant exposure threatens the health of vulnerable residents. Children

living in *ger* districts are exposed to a higher indoor concentration of PM2.5 than children living in an apartment. Therefore, health issues related to the indoor air quality of *gers* should be investigated.

3) Primitive coal stove heating has limited temperature control, which causes excessive heat and large temporal variations. To limit excessive indoor heat and reduce pollutant emission in the near future, coal stoves should be replaced by electrically powered heating devices
4) To facilitate the replacement of coal stoves with electric heating systems, the proposed retrofitting method must widely disseminated. To disseminate the proposed retrofitting system, it is important to enhance the involvement of local stakeholders and demonstrate that the prototype can be applied on a large scale to all households.
5) In addition to the demonstration of the purposed retrofitting method, a numerical simulation model should be developed to reduce the uncertainty and improve the accuracy of the model.

Appendix 1



INTERVIEW QUESTIONNAIRE FOR THE *GER* RESIDENTS

GER #:

DATE OF INTERVIEW:

The individual questionnaire also collected

Section-1 Place

1. Address and zone: These zones are divided by air pollution levels by the Ministry of Planning and Association of Ulaanbaatar. Please refer to Appendix-1.

   Address:

   a. First zone
   b. Second zone
   c. Third zone
   d. Fourth zone
   e. Out of the zone but within a 40 km range from the red line
   f. Outside Ulaanbaatar
2. How well is the *ger* location connected to public infrastructures? Please circle all the connected public infrastructure systems.

   a. Electricity supply
   b. Connected to the Public sanitation system
   c. No public sanitation system, but central sanitation system connection is available
   d. Independent sanitation system
   e. Water supply from *khudag* (water kiosk)
   f. Water supply from Central Water Supply system
   g. Independent deep well
   h. Hot water supply from Central Water Supply system
   i. Central heating system
   j. Central heating system connection is available
   k. Asphalt road that is directly connected to your *ger*
   l. Public transportation

3. If you get your water from Khudag (water kiosk), what is the distance to the transport?

4. If you do not have a direct connection to an asphalt road, what is the distance from the asphalt road to your *ger*?

5. Please circle if there is accessibility between you *ger* and the following public services and write the distance from the service center to your plot.

    a. Kinder garden
    b. School
    c. Hospital
    d. Shopping center
    e. Pharmacy
    f. Post
    g. Communication system (Internet WiFi)
    h. Playground or green area

6. If your area does not have a public garden or green area, is there any space for a playground or green area in your plot?
7. Do you own this plot?

Section-2 Family

1. Please fill in the information about all family members who live in the *ger* house:

	Name & role in family	Sex	Age	Occupation/Job	Education	Relation to the head of the household	Submission of the individual questionnaire (draw)
Member 1							
Member 2							
Member 3							
Member 4							
Member 5							

2. What are the sources of your family income?

   a. Salary
   b. Livestock
   c. Pension
   d. Medical benefits
   e. Infant care allowance

f. Child allowance
g. Business

3. What is the average monthly income of your family? Please be as specific as possible.

   a. Less than MNT 220,000
   b. MNT 220,000–500,000
   c. MNT 500,000–700,000
   d. MNT 700,000–1,000,000
   e. MNT 1,000,000–1,500,000
   f. More than MNT 1,500,000

Section-3 House

1. How long has your family (household) lived in this *ger*?

    a. Less than one year
    b. 1–2 years
    c. 3–5 years
    d. 6–10 years
    e. More than 10 years (Please specify)

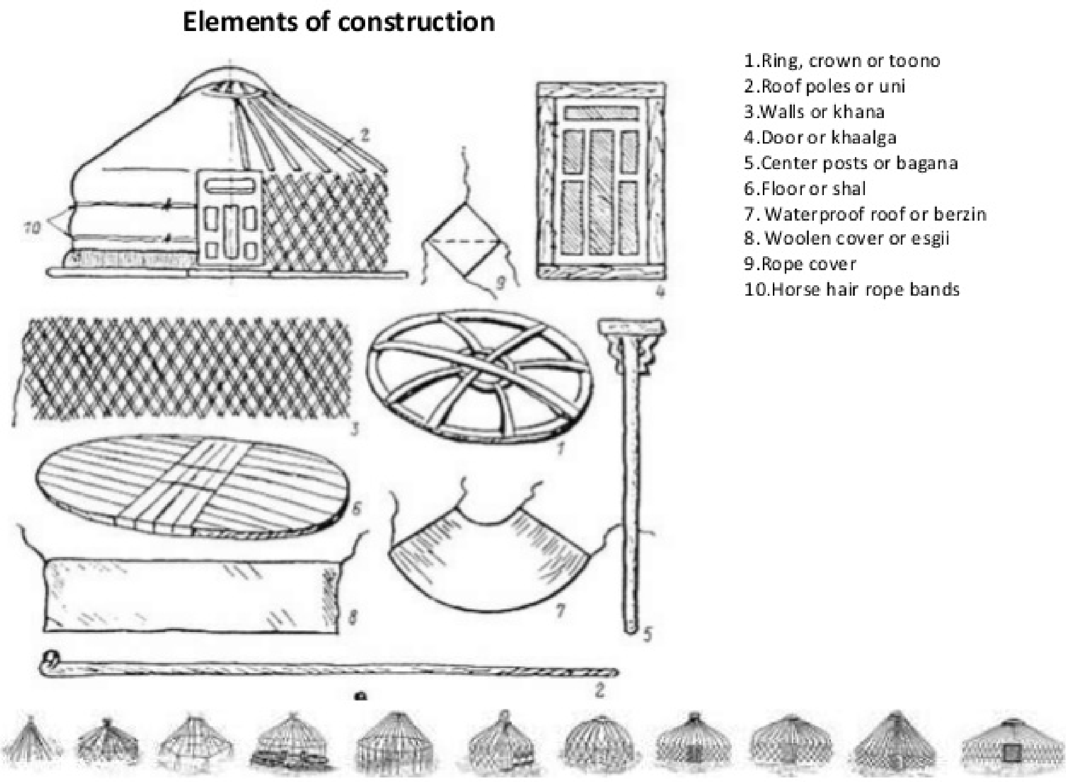
2. How did your family (household) receive the ownership of this *ger*? If you choose options “d,” “e,” “f,” or “g,” please skip questions 7 and 8.

    a. Made by yourself with the help of family members (Please answer question 3)
    b. Bought a new *ger* from the black market or after viewing an advertisement in a newsletter (Please answer question 4)
    c. Bought an old ger from the market or after viewing an advertisement in a newsletter (Please answer question 4)
    d. Someone donated the new *ger* (Please answer questions 4 and 5)
    e. Someone donated the old *ger* (Please answer questions 4 and 5)
    f. Inherited an old *ger* from parents or relatives (Please answer question 4)
    g. It is not my property. It belongs to someone else. (Please answer question 4 and specify a connection to the real owner)

3. If you assembled the *ger* by yourself or with the help of a family member, did you prepare all the parts yourself or did you buy some parts from the black market or from listings advertised in a newsletter? Please specify how you constructed the different parts; alternatively, if you bought the parts from the market, please specify their costs

Detail	How did you construct it	Price	Where did you buy it?
Toono (Skylight)			
Glass for the *toono* (Skylight)			
Uni (Rafter)			
Hana (Lattice wall)			
Door			
Bagana (Pillar)			
Insulation felt			

Outer cover of the roof (Waterproofing layer)			
Outer cover (Waterproofing layer)			
Inner cover of the roof			
Inner cover of the wall			
Floor			
Others			



4. If you bought your *ger* from the black market or based on a listing advertised in a newsletter, how much did it cost? Where did you buy the *ger*? Please specify the price.

5. Why did you lose your previous housing? Did you live in a *ger* previously?

6. Does your *ger* have an antechamber? If yes, what material have you used for the antechamber and is the antechamber used throughout the year?

7. Please specify when you renewed the following parts of your *ger* and the reason for the change? How frequently do you generally renew these parts? What is the cost of these parts in the market? If you have never renewed a particular part of the ger since you started living in it, please leave it blank.

Detail	When did you renew it?	How frequently do you renew it?	Reason	Price
Toono (Skylight)				
A glass of *toono* (Skylight)				
Uni (Rafter)				
Hana (Lattice wall)				
Door				
Bagana (Pillar)				
Insulation felt				
Outer cover of the roof (Waterproofing layer)				
Outer cover (Waterproofing layer)				
Inner cover of the roof				
Inner cover of the wall				

Floor				
Antechamber				

8. In wintertime, do you add more felt layers or covers to your *ger*? If so, please specify.

9. What is the size of your *ger*? If the mentioned floor area is different from the actual size, please choose the wall size and write it behind your chosen answer.

   a. Four walls and

   b. Five walls and

   c. Six walls and

10. When does your family (household) live in the *ger*? Moreover, please specify where you live during the other months.

    a. January
    b. February
    c. March
    d. April
    e. May
    f. June
    g. July
    h. August
    i. September
    j. October
    k. November
    l. December

11. Do you live in the *ger* seasonally. If so, why?
    a. Have a job in an urban area
    b. Difficult to handle an entire year in the *ger*

c. Other reasons (Please specify)

12. How frequently does your family change the location of the *ger*? If you have a different answer, please write it down in the "Others" option.

    a. Never
    b. Once in five years
    c. Once in three years
    d. Once in two years
    e. Once in a year
    f. Twice in a year
    g. Thrice in a year
    h. Four times in a year
    i. Others. . . . .

13. How far do you move when you change the location of your *ger*? If you have a different answer, please write it down in the "Others" option.

    a. In my plot
    b. Outside the city, but within 40 km
    c. Others. . . . .

14. Have you rebuilt your *ger* since you built it for the first time? If you have rebuilt it, how frequently do you rebuild it?

    a. Once in two years
    b. Once in a year
    c. Twice in a year
    d. Thrice in a year
    e. Others (Please specify)

15. Are you interested in changing the condition of your *ger*? If you can change the condition, how much are you willing to pay for the changes?

16. What type of household electronic appliances does you use in your *ger*?

17. What household furnishing are used in your *ger*?

18. How much time do you require to erect your *ger*?

19. What is the winter wall detail?
    a. White artificial cover
    b. Waterproof layer (fiber)
    c. Polyethylene layer
    d. Paper insulation
    e. Felt layer
    f. Polyethylene layer
    g. Inner, white cotton layer
20. What are the characteristics of your floor in winter?
    a. Full carpet
    b. Half carpet
    c. Linoleum
    d. Laminate
    e. Wooden floor
    f. Thin insulation pad
    g. Carton box layer
    h. Insulation for ger floor
    i. Wood chips
    j. Dungs
    k. Concrete
    l. Condensed grave
    m. Normal ground
21. Have you noticed and condensation on your ger envelope?
    a. *Tuurga* (wall felt insulation)
    b. Roof felt layer
    c. Door
    d. Others
22. Have you noticed any water leakage through the *ger* envelope?
    a. Yes
    b. No
23. How do you insulate the floor and wall joints?
    a. Waterproofed felt layer and filled with dirt
    b. Performed waterproofing along with old clothing and blankets and then filled with ground dirt

c. Waterproofed and filled with ground dirt
d. Used floor sack and filled with ground dirt
e. Others

24. How many times do you take out the ashes?
25. How do you choose the felt material for the *ger*?
    a. According to the price
    b. Based on the advice of vendors
    c. Only bought product from government felt factory
    d. Based on the dense nature of the felt
    e. Choose only brown felts
    f. Choose felts with less smell
    g. Others
26. How do you choose the waterproof material for the *ger*?
    a. According to price
    b. Based on the advice of vendors
    c. Select fiber pieces
    d. Others

Section-2 Heating device and Activity information

1. What type of heating device do you use in your *ger*? You can choose more than one answer. (If you choose only option "a," please skip question number 2; if you choose any other option, please skip question number 3)

	Heating device	Details	Years of usage
a	Electric heating device		
b	Improved stove (*ulzii* etc.)		
c	Coal-burning stove		
d	Others		

2. What type of fuel do you use in your stove? Please write the number of kilograms or tons (porter) you use in a year. If you use more than one type of fuel, please specify all the types.

		Yearly usage (in kg)
a	Raw Coal	
b	Wood	
c	Smokeless fuel	
d	Others	

3. What type of electric heating device do you use? What is your monthly electricity payment during the winter season?

		Monthly payment (MNT)
a	Underfloor heater	
b	Radiant heater	
c	Fan heater	
d	Storage heater	
e	Others	

4. If your stove is a traditional coal-burning stove, do you want to improve your stove? How much can you pay for a new stove?

5. If you are using the improved stove, how satisfied are you with this stove?
   a. Very satisfied
   b. Satisfied
   c. Slightly satisfied
   d. Slightly unsatisfied
   e. Unsatisfied
   f. Very unsatisfied

6. When does your family use the heating device? Please circle the months when the heating device is used.

   a. January

b. February
c. March
d. April
e. May
f. June
g. July
h. August
i. September
j. October
k. November
l. December

7. While using the heating device, do you control the temperature of the room? What is your setting temperature? Do you change the temperature setting depending on your activity?

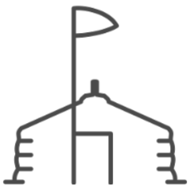
8. Do you use the heating device throughout the day in winter? Or do you used it only partially?

00:00 01:00 02:00 03:00 04:00 05:00 06:00 07:00 08:00 09:00 10:00 11:00 12:00

13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00 24:00

9. Have you considered the air quality in your *ger*? Do you use an air purifier or any other equipment to improve the air quality?

10. Do you use any cooling device in summer? If yes, please specify the months and the type of cooling device that is used.



BEHAVIOR AND COMFORT QUESTIONAIRE FOR *GER* RESIDENTS

***Ger* #:**

Date and Time:

Section-1 General information

1. What is your relation to the head of your household?

   a. Household head
   b. Partner
   c. Children
   d. Grandchildren
   e. Father/Mother
   f. Father-in-law/Mother-in-law

g. Grandparents
h. Grandfather in-law/Grandmother-in-law
i. Siblings
j. Siblings-in-law
k. Other relatives
l. Not a relative

2. Name

3. Age:

4. Gender:
5. Occupation:
6. Educational level:
    a. Graduate degree
    b. Undergraduate degree
    c. Vocational school
    d. High school
    e. Secondary school
    f. Primary school
    g. Not educated

7. Address:

8. Do you live in the *ger* for the entire year or seasonally?

    a. January
    b. February
    c. March
    d. April
    e. May
    f. June
    g. July
    h. August
    i. September
    j. October
    k. November
    l. December

Section-2 Winter occupant behavior and comfort

1. How do you feel about air humidity?
   a. Very dry
   b. Dry
   c. Neutral
   d. Sticky
   e. Very sticky
2. What type of clothing do you wear in winter in a *ger*? How many layers do you wear? What is the thickness of the material and are you aware about thermally insulated clothing?

   a. Cotton bodysuit
   b. T-shirt
   c. Tank tops
   d. Jacket
   e. Short skirt
   f. Jeans or trousers
   g. Insulated vest
   h. Sweater
   i. Hoodies
   j. Puffer
   k. Long skirt
   l. Insulated pants
   m. UGG boots or fur shoes
   n. Boots
   o. Desert boots
   p. Insulated sleepers
   q. Socks
   r. Baseball Hat
   s. Woolen hat
   t. Scarf
   u. *Deel* (traditional costume)
   v. Others

3. When you are sleeping, do you wear the same clothes that you wear in the daytime or do you change to pajamas? If you change to pajamas, what is its thickness?

4. How many layers of blankets do you use when you are sleeping? Please specify the thickness of the blankets.

5. Do you sleep on the bed or the floor? What is the thickness of the mattress and futon?

6. Which part of the *ger* do you usually stay in?

7. Where do you usually sit?
   a. On the bed
   b. On the floor
   c. Cushion
   d. Tiny wooden chair
   e. Sofa
   f. Armchair
   g. Chair
   h. Others

8. In the winter months, how do you feel about the indoor environment in the *ger*?

   a. Very comfortable
   b. Comfortable
   c. Slightly comfortable
   d. Slightly uncomfortable
   e. Uncomfortable
   f. Very uncomfortable

9. When you feel uncomfortable, would you describe the temperature as too hot or too cold?
   - Too cold
   - Too hot

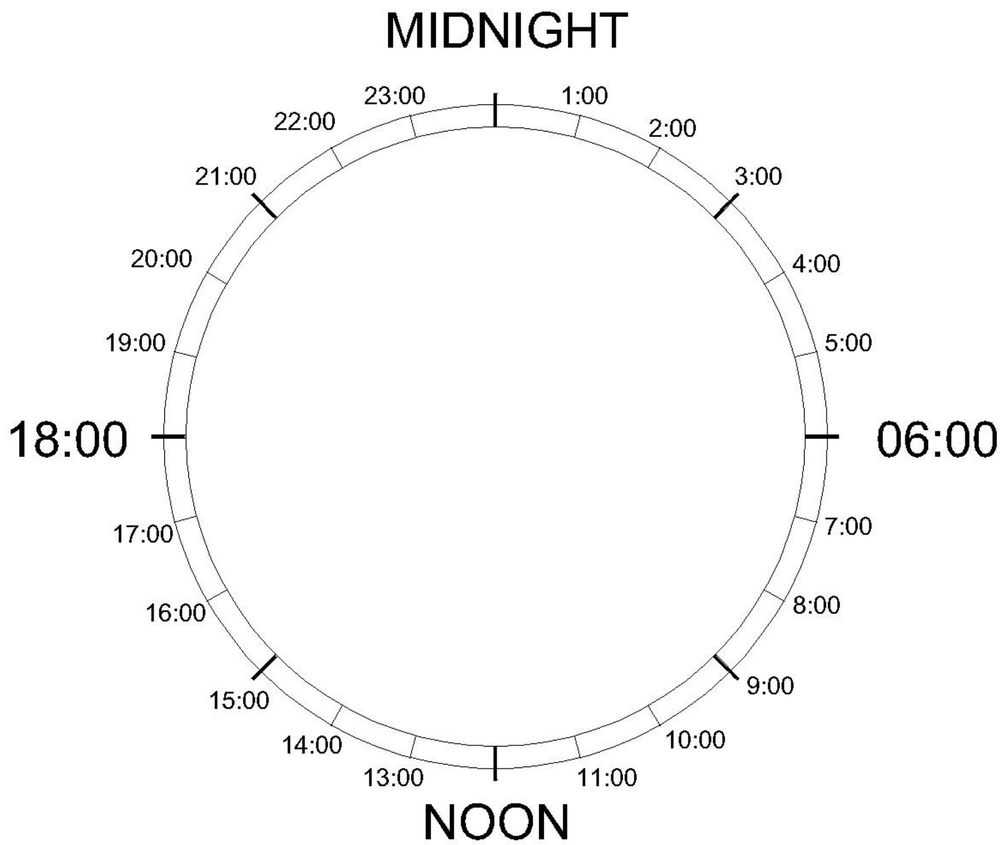
10. When you feel uncomfortable, please describe the source of your discomfort.

    a. Too much air movement

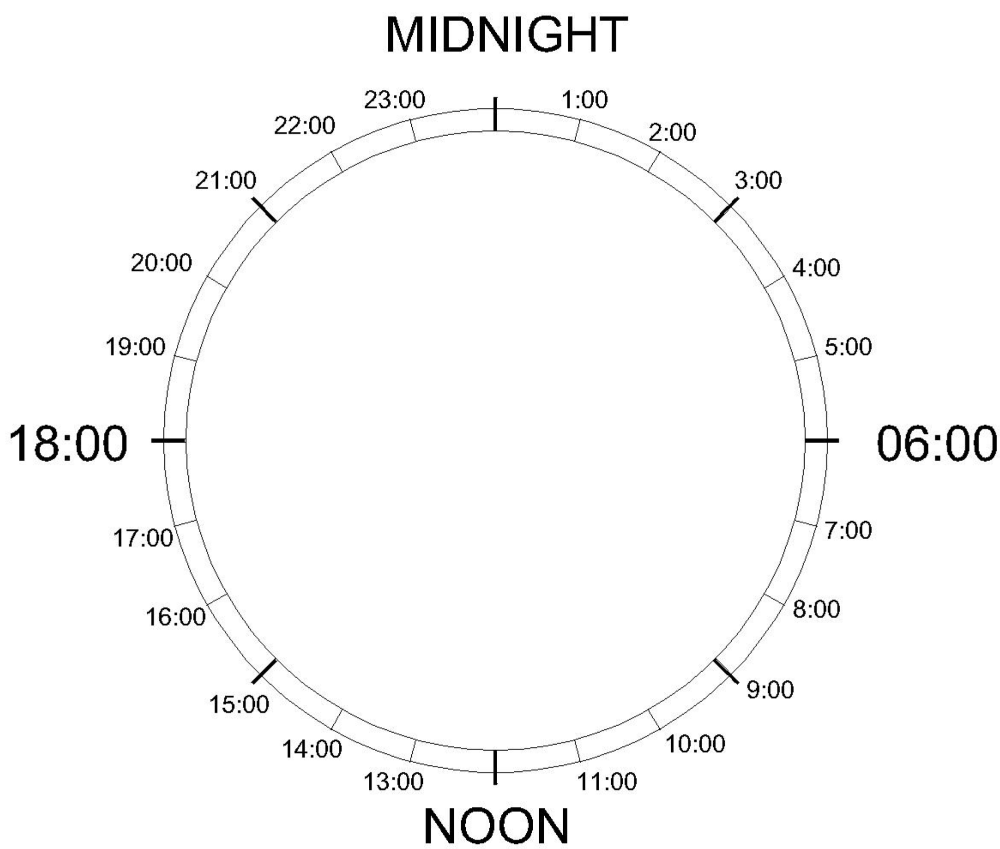
b. Not enough air movement
c. Incoming sun
d. Hot/cold surrounding surfaces (floor, ceiling, walls, etc.)
e. Excess heat from the heating device
f. Heating device does not respond well
g. Uneven temperature distribution (some parts are always hot, while some parts are always cold)
h. Others (please specify)

Section-3 Winter daily schedule

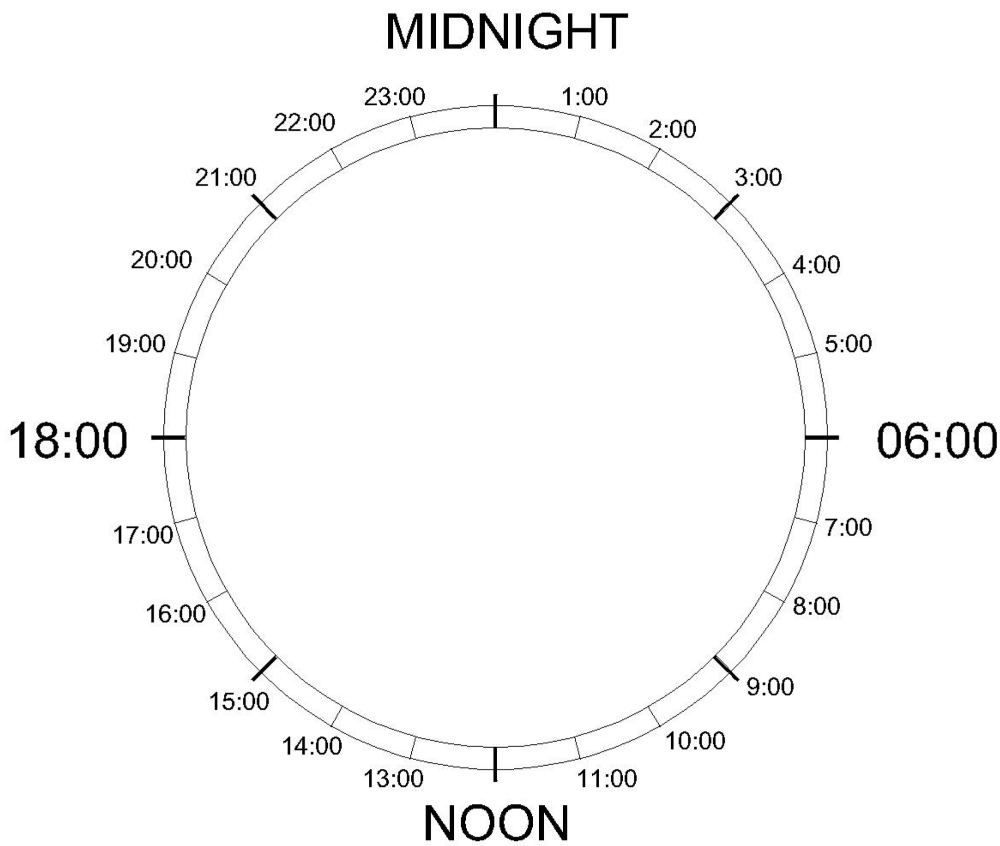
1. Please describe your daily schedule on weekdays



2. Please describe your daily schedule on weekends



3. Please describe your daily schedule on holidays



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