Development of a software tool for decision-making on HVAC systems' capacity for military tents

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DEVELOPMENT OF A SOFTWARE TOOL FOR DECISION-MAKING ON HVAC SYSTEMS' CAPACITY FOR MILITARY TENTS

AGATA RIJS

Development of a software tool for decision-making on HVAC systems’ capacity for military tents

Agata Rijs

07-07-2020

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Stan Ackermans Institute

SMART BUILDINGS & CITIES

Development of a software tool for decision-making on HVAC systems' capacity for military tents

By

Agata Rijs

A dissertation submitted in partial fulfillment of the requirements for the degree of

Professional Doctorate of Engineering

The design described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct

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EXECUTIVE SUMMARY

This PDEng project was initiated by The Dutch Ministry of Defense. The aim of this project was to design and develop a software tool supporting the decision-making on HVAC systems' capacity for military tents.

Military missions and training take place all over the world, very often in countries where the weather conditions are extreme. During missions, soldiers live and work in temporary infrastructure, especially in military tents. The tents act as sleeping quarters, relaxation rooms, dining halls, offices, storages, field hospitals, or even hangars. To ensure an acceptable indoor environment, the tents are equipped with heating, ventilation, and air-conditioning systems (HVAC). While preparing a military mission or training, it must be decided what capacities of the HVAC systems must be provided. The decision is difficult because of the large variety of factors influencing the choice, such as characteristics and intended function of a determined tent, and local weather conditions. Moreover, the decision is usually made by experienced and technically-skilled people, whose core activities are not necessarily related with HVAC systems.

To support these decision-makers with their task, this project delivers a decision-support tool (DST) that provides information about the required capacity of the HVAC system, the consequences of the application of a lower-capacity system, cooling and heating energy demand, thermal comfort and safety. This tool meets requirements that were identified in the requirements specification process.

The requirements specification process was an important part of this project. This specification was realized with the use of some techniques that helped to organize information that was collected during interviews with the advisor from The Defense Organization responsible for this project. These requirements established that the DST to be delivered at the end of this project would be user-friendly, flexible, and reliable. User-friendly means that it should be fast and intuitive for the user. Moreover, the DST inputs must be limited to the information that the user can collect and the outputs should provide the necessary information but not be confusing. Flexible means that it must cover a wide range of possible cases. Reliable means that it must provide correct results. These three requirements are conflicting with each other. Therefore, the main challenge of the project was to find the right balance between them.

The developed DST has the following advantages:

- The DST input form was developed in MS Excel, which is a software that the client is familiar with. The input form contains short instructions explaining how to fill in each input cell. It also includes default settings to make it easier to fill it in. However, if the user wants to go beyond the default settings, it is also possible to fill in additional, more detailed input cells, that make the DST very flexible.
- The DST has been built on top of a well-known and reliable building performance simulation program. The model considers the dynamic interactions between the tent, occupants, equipment, weather conditions, and the HVAC system. The user can run the simulation directly from the Excel input form by one click. The fact that the user can run the simulation by himself provides large flexibility and enables the calculation of an unlimited number of possible cases.
- The DST provides results in a PDF report format. The report containing information that is crucial for HVAC systems sizing is automatically displayed to the user. The information allows the user to

make a risk-aware decision instead of deciding for the user. If the user wants to get information about energy demand, thermal comfort, or heat stress risk, he can open an additional output report by one click in the input form.

- The DST can be used for the sizing of HVAC systems but also for demonstrating the effects of weather conditions, tents' properties, and shading application on the thermal comfort and heat stress risk in military tents.
- The DST provides extensive user support.
- The DST is also future-proof, it can be used for tents currently owned by the Dutch army as well as tents that will be purchased in the future.

As shown above, the mandate of this project to develop a user-friendly, flexible, and reliable software tool for decision-making on HVAC systems' capacity for military tents was achieved.

ACKNOWLEDGEMENTS

The great experience of being a PDEng trainee at the Eindhoven University of Technology has come to the end. It was an honor and pleasure to be one of the Smart Buildings and Cities PDEng trainees. The traineeship enabled both my personal and professional development. I have learned a lot and I met many great people.

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Last but not least, I express my gratitude to my family for their support, motivation, and faith in me.

ACRONYMS

HVAC - Heating, ventilation, and air-conditioning
DST – Decision-support tool
BPS – Building Performance Simulation
MCA – Multi-criteria analysis
SBD - Shading:Building:Detailed object in EnergyPlus
WMS - WindowMaterial:Shade object in EnergyPlus
AGL – Additional glass layer
NS – No shading
TMY – Typical meteorological year

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1 INTRODUCTION

1.1 PROBLEM DESCRIPTION

Military tents are used for missions, training, and emergency crises all over the world in various – sometimes extreme – climates. They serve functions such as field hospitals, office rooms, sleeping quarters, storages, hangars for fighter planes, etc. They differ in size, function, and construction. In order to guarantee acceptable indoor conditions, the tents are equipped with heating, ventilation, and air-conditioning systems (HVAC).

For each use of the military tents, the decision must be made which climate control system will be sent. It is unacceptable to underestimate the HVAC system capacity because it may lead to thermal discomfort, harmful or unhealthy indoor conditions, or to a failure of some equipment due to overheating or freezing. The oversizing of the HVAC system has also numerous negative consequences. Oversized systems' operation is unstable. It means that the system starts up and shuts down more often because it runs for a short time to meet the setpoint temperature. This leads to a shorter lifespan of the system and more often failures. Moreover, the energy consumption of an oversized system is larger because the system needs more power when it starts up than when it is running. Also, unstable operation makes the system control difficult. Military HVAC systems are driven either by liquid fuels or by electricity produced by diesel generators. Since the energy consumption of an oversized HVAC system is higher, more fuel is needed. The fuel delivery is logistically difficult and expensive. Considering the cost to deliver the fuel to some isolated places in the world ensuring security, reduction of fuel consumption leads to substantial savings. Also, while using oversized systems, the inventory of the army is inefficiently managed. Systems of small capacity are not used because of the concern that their capacity is not enough. Therefore, sometimes unnecessarily large systems are sent to distant, isolated locations. The transport of these big systems and sufficiently large diesel generators is logistically more difficult and expensive than in the case of smaller systems. Also, the cost of purchasing large-capacity systems is higher. An additional disadvantage of oversized systems is the noise they make that is very annoying for the tent occupants.

The decision-makers who prepare missions find it difficult to select the size of the HVAC system that is appropriate for a given temporary structure, its properties, function, location, and weather conditions. The decisions sometimes concern climate control systems from the army's own stock and sometimes also the purchase of new devices.

Military tents are a unique type of buildings because of, for example, their relatively large volumes, light permeability of the envelope, interactions with the ground, no internal partitions, possible thermal stratification, intensive infiltration, almost no thermal mass, and no insulation. These factors have a great influence on heat gains and heat losses. These factors are not compatible with commonly used HVAC sizing methods, which were primarily developed for office buildings. These existing methods cannot simply be used for tents because of their quite different conditions and characteristics. The lack of insight into how the selection process of climate control systems for tents could be optimized and the lack of tools available to facilitate the decision-making were the motivation for this PDEng.

1.2 PROJECT SCOPE AND OBJECTIVES

The mandate from the Dutch army for this PDEng project was to design and develop a software tool supporting the decision-making on the HVAC systems' capacity for military tents. The decision-support tool (DST) is required to calculate a wide range of possible scenarios and is intended to be used by technically skilled people, whose core activities are not necessarily related with HVAC systems.

The scope of the project included requirements specification, determination of the calculation method, and incorporation of the method into a user-friendly software tool. To meet the design requirements for the tool, the DST inputs and outputs were tailored to the needs of the intended end-users during the design process.

1.3 REPORT OUTLINE

The outline of this report is presented schematically in Figure 1. This report contains results at different levels and subjects. Not everything is equally useful for each reader. For readers interested only in the project objectives and the final deliverable, it is recommended to read chapters 1, 7, and 8 (highlighted in red in the scheme shown in Figure 1). Readers who are also interested in the design and development process are advised to read the whole report.

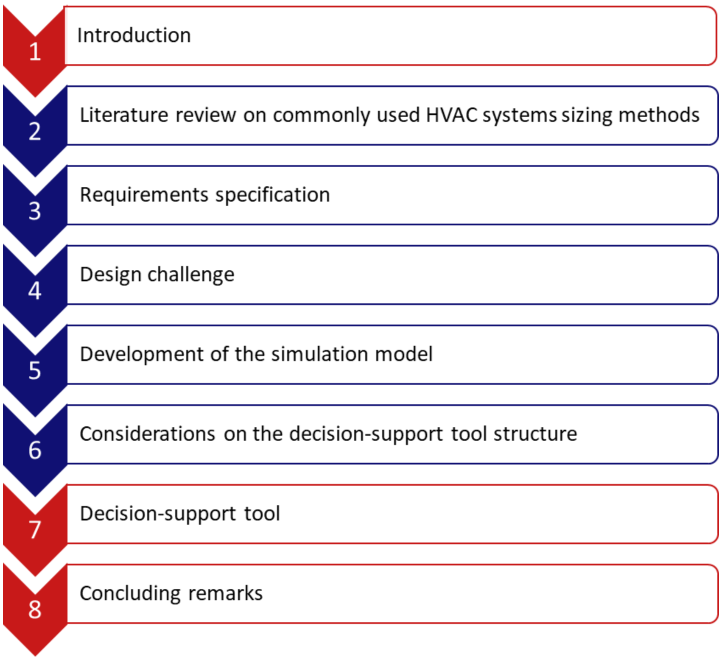


Figure 1 Report outline

Chapter 2 of this report presents a review of commonly used HVAC system sizing methods. The methods are briefly described and the reasons why they are not suitable for tent appliactions are discussed.

Chapter 3 describes the requirements specification process and presents the identified requirements. Generalizing, the DST is required to be user-friendly, flexible, and reliable. Since these three desired features are partially conflicting, incorporation of them in the DST poses the main design challenge which is described in section 4. The challenge was taken up on three levels.

One of the levels was the tent simulation model development described in chapter 5. Thermal modeling challenges of tents were identified based on the literature review. Then, extensive analyses were performed to determine the most suitable modeling approach for this project.

Another level was the decision on the DST structure discussed in chapter 6. The question was if the DST should be a database with a user-interface allowing searching for a datapoint or rather an interface enabling the user to run real-time calculations in an easy way. A few options for the DST structure were considered, the pros and cons were analyzed, and the final decision was made.

The third level was the design of the DST input and output described in chapter 7. The section describes also the DST operation, explains design decisions, and provides illustrative use cases. Therefore, if somebody is interested only in the final product of this project, he/she should go directly to chapter 7.

Chapter 8 summarizes the main outcomes and discusses how the DST solves the problem formulated by The Dutch Ministry of Defense. Also, it discusses some limitations of the DST and future work.

2 COMMONLY USED HVAC SYSTEMS SIZING METHODS

HVAC systems are most commonly sized on the basis of heating and cooling load calculations. The loads are calculated from heat losses and gains in the building. Two components of the heat losses can be distinguished. The first component is the transmission heat loss which is the heat loss to the exterior or an adjacent space resulting from conduction through the building surfaces (walls, roof, floor, windows, doors). The second component is the ventilation heat loss which is the heat loss to the exterior resulting from ventilation and infiltration. The heat gains originate from solar radiation entering through transparent surfaces, conduction through the building envelope, conduction between adjacent spaces, ventilation, infiltration, and heat generation by occupants, lights, and equipment. One of the main goals of HVAC systems is to maintain the indoor temperature on a defined level. In order to do this, the systems need to have enough capacity to provide the amount of thermal energy that is needed to cover heating or cooling load.

There are various methods of heating and cooling loads calculations differing in complexity. The methods are proposed either by national standards (for example EN, NEN, DIN) or by guidelines developed by professional associations (for example ASHRAE, ISSO).

Heating load calculations are performed to arrive at the required heating capacity. The peak heating load normally occurs in winter before the sunrise. Therefore, solar heat gains are not included in the peak load calculations. In Europe, the heating load calculation method proposed by the standard (EN 12831, 2017) is most commonly used. The method is set up to calculate the heating load under design (worst-case) conditions. Heat losses are calculated in steady-state conditions assuming constant temperatures and building elements characteristics. Moreover, air temperature and operative temperature are assumed to be equal. The first step of the calculation procedure is to determine the design external temperature, the annual mean external temperature, and the internal design temperature for each space. The annual mean external temperature is used to calculate heat losses through the ground. The second step is to define the dimensions and characteristics of all building elements. After that, transmission, ventilation, and infiltration heat losses in the design conditions can be calculated. Later, the heating-up capacity is calculated. The heating-up capacity is the additional power needed to compensate for the effects of intermittent heating. Finally, the total design heat load is obtained by the addition of the design heat losses and the heating-up capacity. The method neglects internal heat gains to account for the worst-case conditions. A similar method is proposed by (ASHRAE, 2009).

When it comes to cooling loads calculations, there is no single widely-accepted calculation method. There are many methods proposed by national standardization organizations or professional associations. The cooling load calculations are much more complex than the heating load calculations. According to (ASHRAE, 2009), the cooling load calculation can never be more than a good estimate. A precise calculation is impossible due to variation in the building materials properties, the quality of buildings construction, or the way the building is operated. Moreover, there are numerous variables affecting cooling load which are often difficult to define precisely and always intricately interrelated. Cooling load components vary in magnitude during a day cycle and the cyclic changes are not in phase with each other. Cooling load is the rate at which heat must be removed from the building to maintain the desired constant air temperature. It cannot be directly calculated as the sum of all instantaneous heat gains due to the fact that radiant heat gains contribute to the cooling load with a delay. Radiant energy is first absorbed by the surfaces enclosing the space and objects in the space. When their temperature increases above the surrounding air temperature, heat is convected to the air. The heat storage capacity of the surfaces and objects determines the rate of their temperature increase.

The cooling load calculation methods provided by national standards are usually either steady-state calculations (for determined design conditions) or calculations performed for each hour of a design day. The weather parameters for the design conditions or the design day are provided by the standards. The calculation procedure includes calculation of both internal heat gains (from people, lights, equipment, and transmission from adjacent spaces) and external heat gains (from transmission, solar radiation, infiltration, and ventilation). To account for the time delay effect described in the previous paragraph, different kinds of accumulation factors are used. The values of the factors were determined experimentally for typical constructions of building elements. The impact of solar radiation on the transmission heat gains is considered by the use of an equivalent external temperature (sol-air temperature (ASHRAE, 2009)). In The Netherlands, there are two cooling load calculation guidelines – a more detailed one described by (NEN 5067, 1985) and less detailed provided by (ISSO, 2010).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2009) proposes three cooling load calculation methods. The simplest approach is the CLTD/GLF method (Cooling Load Temperature Difference / Glass Load Factor). The CLTD factor represents the temperature difference between outdoor and indoor considering also the effect of solar radiation. The GLF represents the total heat gain through windows per square meter. The CLTD/GLF method involves steady-state calculations for determined design conditions. The heat accumulation is not considered. Tabulated values of CLTD and GLF are provided for light, medium, and heavy constructions and specific glazing types. The CLTD and GLF values are dependent on the surface orientation, the daily temperature range, and the design external temperature.

The ASHRAE Heat Balance (HB) method falls into the category of detailed methods. Cooling load calculation involves a surface-by-surface conductive, convective, and radiative heat balance for each surface and a convective heat balance for the room air. The HB method solves the problem directly instead of using transformation-based procedures. There are no arbitrarily set parameters – all parameters have a physical meaning based on first principles. However, some assumptions were made. The air in the thermal zone is modeled as well mixed, the surfaces of the room have a uniform surface temperature, the long-wave and short wave irradiation is uniform, there is one-dimensional heat conduction, and the radiating surfaces are diffuse. Figure 2 presents four distinct processes that are included in the method: outside-face heat balance, wall conduction process, inside-face heat balance, and air heat balance. The three first processes are repeated for each surface enclosing the zone (ASHRAE, 2009). The heat balance approach is applied in Building Performance Simulation (BPS).

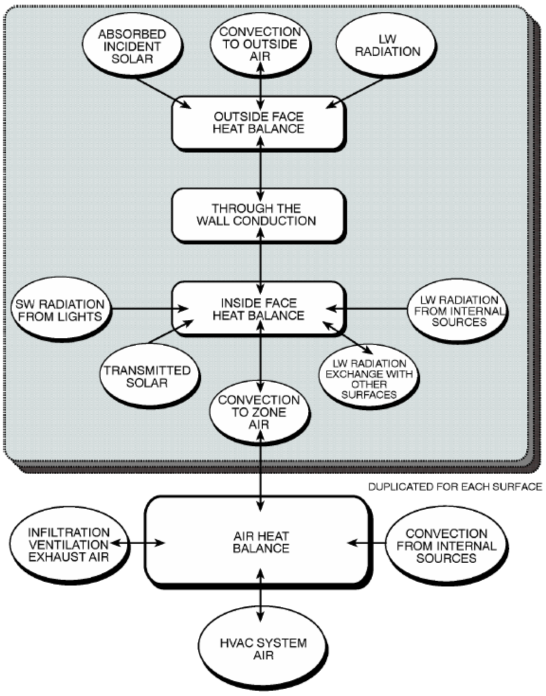


Figure 2 Schematic of Heat Balance Processes in a zone (ASHRAE, 2009)

The ASHRAE Radiant Time Series (RTS) is a simplified method derived from the HB method. However, still the load prediction using this method requires a complex computer program. The method simplifies the HB method by relying on an estimated radiative/convective split of wall and roof conductive heat gain instead of simultaneously solving for the instantaneous convective and radiative heat transfer from each surface. This method does not require iterative calculations and considers each component contribution to the total cooling load. In the RTS method, steady-periodic conditions (the design day’s weather, occupancy, and heat gain conditions are identical to those for preceding days such that the loads repeat on an identical 24 h cyclical basis) and two time-delay effects are assumed (delay of conductive heat gain through massive exterior surfaces and delay of radiative heat gain conversion to cooling loads). The time-delay effects are accounted for by multiplying hourly heat gains by 24 h time series. Series coefficients called radiant time factors and conduction time factors are derived from the HB method. In this method, cooling loads of each component for each hour are calculated and summed to determine the total cooling load for the hour. The cooling load for each component for each hour is the sum of the convective portion of radiant heat gains for that hour and the time-delayed portion of radiant heat gains for that hour and the previous 23 h. Then the hour with the peak load is selected for the design of the HVAC system. Radiant time factors are generated by a heat balance based procedure. For most common design applications, RTS values depend mainly on the thermal mass of the construction and the thermal responsiveness of the surfaces subjected to the radiant heat gains. Representative RTS data for light, medium, and heavyweight constructions are provided by ASHRAE. Customized RTS values may be calculated using the HB method when the zone is not reasonably similar to these typical zones or where more precision is needed (ASHRAE, 2009).

To conclude, all the simplified calculation methods involve the use of various factors which are precalculated and tabulated. The factors are calculated for predefined conditions such as indoor and outdoor temperatures, surface orientation, or building elements characteristics. The predefined conditions reflect situations that are typical for conventional buildings. Therefore, the applicability of these simplified methods is limited to conventional buildings. Since tents have distinct thermal characteristics that are fundamentally different from conventional buildings, the simplified methods are not suitable for their heating and cooling load calculations.

Furthermore, the simplified methods involve some simplifications that do not lead to a significant inaccuracy when used for conventional buildings but for tents their impact on the accuracy could be large. For example, the heating load calculation method proposed by (EN 12831, 2017) assumes that the ground temperature is equal to the annual mean external air temperature and the heat loss to the ground is calculated using this temperature and a correction factor. A conventional building, especially high-rise, having an insulated floor, or a basement or a crawl space is not significantly affected by the ground heat transfer, especially because the presence of the permanent building also reduces the temperature changes of the ground below the building. For a tent, which is an extremely light-weight building, the ground is the only component having significant thermal mass. Moreover, the tent's floor has usually very low thermal resistance. Also, the tent is a temporary structure that does not moderate the temperature changes of the ground. Therefore, for tents, the simplified calculation of the ground heat transfer could lead to a large inaccuracy.

Also, the simplified methods are steady-state or design day calculations assuming the worst-case scenario. This approach is rather deterministic and can lead to oversizing of the HVAC system during the majority of the year. The DST should enable the user to make an informed and risk-aware decision rather than deciding for the user. Therefore, it would be beneficial to calculate the annual heating and cooling loads so that the user could understand the consequences of the application of a system of a lower capacity than the peak demand.

Because of all aforementioned reasons, it was decided to use for this project the dynamic building performance simulation (BPS) that performs the heat balance calculations for the whole year considering the dynamic interactions between the building, weather, occupants, equipment, and HVAC system. BPS is intended for conventional buildings. Therefore, a literature review, analyses, and tests were needed to determine the tent modeling strategy. This strategy should not always account for the worst-case assumptions in order to prevent the oversizing of the HVAC system. The oversizing is undesired for the reasons described in section 1.1.

3 REQUIREMENTS SPECIFICATION

3.1 METHODS

The function of the DST is to support the decision-making on HVAC systems' capacity for military tents. The DST must be designed taking into account its use context and the users' needs. Therefore, requirements specification is a crucial step in the design process answering the question how the DST should fulfill its function. Answering this question is only possible if good cooperation and communication between the designer and the users are pursued.

In order to define the requirements, requirements specification techniques were applied as can be seen in Figure 3. Information was collected during interviews with the company advisor and the tool user in the same person. The collected information was directly translated to non-functional requirements and used to create personas. In the next step, following the suggestion given by (Cohn, 2009), user stories were written for the personas. In the last step, list of functional requirements was extracted from the user stories. In the following subsections, each step is elaborated.

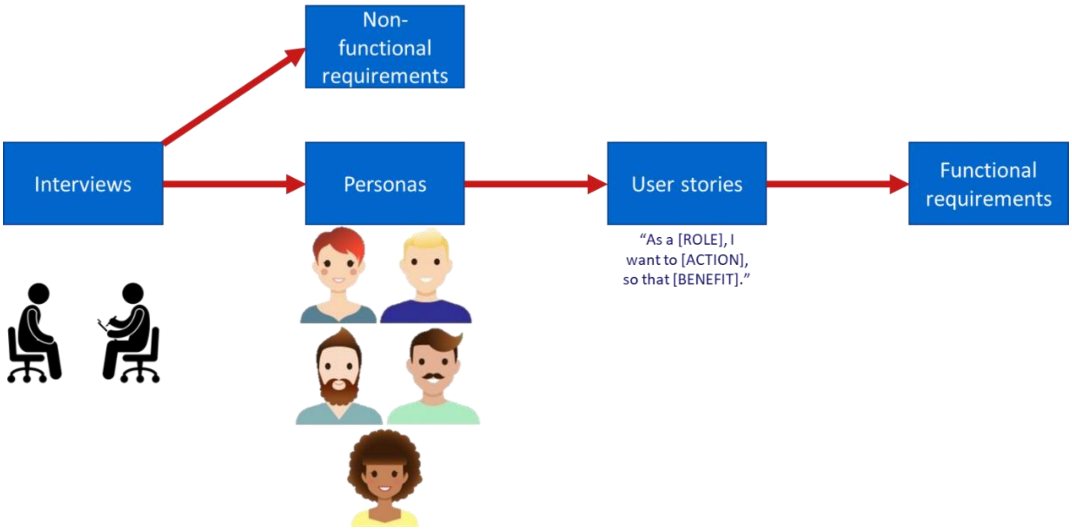


Figure 3 Requirements specification process

INTERVIEWS

During the first interview, several questions were answered allowing to understand the context of the tool use and the end-user problems. The answers are shortly summarized below.

What is the current situation?

The Ministry has different types of tents. For some of them, shading can be applied. The tents are used for missions and training all over the world, often they are exposed to extremely hot or extremely cold weather conditions. Sometimes they are also used in the Netherlands for some events. They are usually equipped with climate control systems. Sometimes the climate control systems are assigned to the tents by suppliers and sometimes the tents and climate control systems are purchased separately. For each application of the tents, a climate control system must be selected. Currently, the decisions are not informed, are made intuitively, based on experience or supplier's suggestions.

What are the current needs and problems?

Because the decisions are not informed, it often happens that the climate control systems' capacity is under- or overestimated. If the capacity is underestimated, the soldiers complain about thermal discomfort in tents. Moreover, some equipment stored in the tents may be damaged due to overheating or freezing. If the systems are oversized, the soldiers complain about noise, energy efficiency of the system is low, the inventory is inefficiently managed, and the investment and operational costs are higher. In the case when suppliers assign the climate control systems to the tents, usually the capacity is underestimated. Probably the suppliers do not take into account internal gains and the impact of extreme climates.

What is the context of the tool use?

The tool is supposed to support the decision-making concerning the climate control systems' capacity for military tents. The tool will be used during preparations of military missions, training or other events for which military tents equipped with the climate control systems are used.

Who is the end-user and what are the end-user's goals?

The end-users of the tool are not diverse. They are the people who decide which tents and which climate control systems are used for a specified application. They are technically skilled, but they are not professionals in climate control systems. If they are satisfied with the tool, they will share it with other departments of the Ministry of Defense.

The goal of the end-users is to make good decisions concerning the climate control systems. They want to avoid tents occupants' complaints about thermal discomfort. They also want to provide a healthy and safe indoor environment for the occupants. The end-users would like to have control over the indoor air temperature setpoint so that it can be adjusted to the ambient temperature and to the tent's function. The end-users want to manage the inventory in an informed and efficient way. Moreover, the purchase department has the opportunity to buy tents and climate control systems separately and they want to be sure that they buy the right things.

What is the equipment the end-user works with?

The tents have various shapes, sizes and are made of various materials. Technical specifications of a few typical tents were provided. The tents are heated and cooled by mobile heaters and air-conditioners. The mobile heaters are powered by liquid fuels such as diesel or kerosene. The air-conditioners can be connected to the mains power supply or to a separate diesel generator. The heaters and the air-conditioners are equipped with supply and return air ducts which can serve one or two tents.

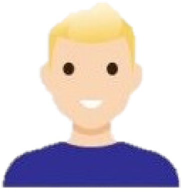
The interview conducted during the introductory meeting with company advisor allowed answering the basic questions. The collected information helped to better understand the background. This was a good base to start the requirements specification process. After the requirements specification process started, new questions were emerging, e.g. What kind of information is available for the tool user based on which he can select the proper HVAC system? What information is lacking or can be obtained with effort? What is important for the client – energy consumption, comfort, costs, space, reliability? In order to address these questions, the second interview with the advisor from The Ministry was conducted.

The information collected during the second interview was very extensive and rather unorganized. In order to facilitate sense-making and communication, personas were created.

PERSONAS

The use of personas in design was firstly introduced by (Cooper, 1999). Personas are a fictional representation of particular users of a product. They are a way to visualize all the user data that was gathered and include users' motivations, frustrations and the essence of their situation and related problems. Personas are based on real users. They help to understand who the product is designed for and therefore can be used to make key design and functionality decisions. Personas are also useful for communication between stakeholders. (Mears, 2013) They are often used by technological designers and human-technology interaction researchers to describe users (Mulder & Yaar, 2006), (Pruitt & Adlin, 2006), (Courage & Baxter, 2005), (Chapman, Love, Milham, ElRif, & Alford, 2008), (Turner, Reeder, & Ramey, 2013).

For this project, personas were used as a way to structure and converge the collected pieces of information. They are presented below.

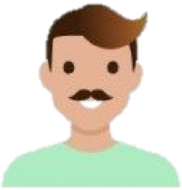


Ben

Ben is a technician working for the Ministry of Defense. He was asked to prepare 300 multi-purpose tents (MPT II) for a mission in Mali. Ben is a prudent person. The climate in Mali is extremely hot. Ben does not want to provide an oversized system because he does not want to give the soldiers the opportunity to set too low temperature in the tents in order to prevent health problems caused by the temperature shock. Moreover, oversized systems make noise and consume more fuel. Larger fuel consumption causes additional costs and the need to refill the fuel tank more often, which is not convenient. Ben wants to size the HVAC system properly so that there are no complaints and the soldiers' health is protected. Also, he wants to convince the soldiers to install shading so that the cooling demand and fuel consumption is decreased.

Jasper

Jasper is a technician working for the Ministry of Defense. He prepares a training in Germany. The training is organized in summer and lasts three weeks. He is going to send a tent which is going to serve as a canteen. Jasper knows that the tent can host 300 people and that the only equipment in the tent is the lighting. Jasper wants to use this information to size the HVAC system accurately.



Jan

Jan is a technician working for the Ministry of Defense. He prepared tents and air-conditioning systems for a mission in Afghanistan. After one month, he received a complaint from soldiers that it is too hot in their tents. Jan sent the largest available air-conditioners and he cannot do anything more. Jan wants to prove that he did his best and to show that it is not possible to provide thermal comfort in tents in such an extremely hot climate.


Floor

Floor is a technician working for the Ministry of Defense. Every year she cooperates with the Dutch Land Forces in The Four Day Marches preparation. The Four Days Marches always take place in summer in Nijmegen. Floor is responsible for the arrangement of tents. She discusses with the event organizers from the Land Forces how many and what type of tents is necessary. They also discuss the tents' function and the required indoor temperature range. After that, they write a program of requirements. Based on the program, Floor arranges AD Boog tents from the inventory. The tents serve as administration offices. So far, the tents have never been air-conditioned. Because of many complaints, Floor would like to provide air-conditioning to the AD Boog tents. However, because of the lack of previous experiences, she does not know what cooling capacity is needed. The tents are old and the manufacturer is unknown, therefore she cannot ask him for advice. Besides the small AD Boog tents, Floor rents additional tents from a tents rental company. Usually, she signs a contract with the company for four years. The company provides tents together with HVAC systems. Because of negative previous experiences, Floor is not sure if the provided systems' capacity is appropriate. She would like to have the opportunity to double-check it.


Anne

Anne is a purchase officer working for the Ministry of Defense. She purchased new tents. HVAC systems are included in the set. Anne wants to make sure that the HVAC systems that are proposed by the supplier are suitable for the purchased tents and for their intended applications.

USER STORIES

The next step was to write user stories for the created personas. The user stories are informal descriptions of the product features. They are written from the perspective of the end-user. The user-stories help to further organize the collected information and to get a deeper understanding of what is needed. The stories help to form the first mental image of the product. According to (Lucassen, Dalpiaz, van der Werf, & Brinkkemper, 2016), the adoption of user stories is growing especially in the software development. The most common user stories template is the Connextra template which is based on the structure "As a [ROLE], I want to [ACTION], so that [BENEFIT].". User stories are considered by many authors of software development and requirements engineering handbooks as an effective method to identify user-valued product functionalities and features (Cohn, 2009), (Patton & Economy, 2014). The user stories are listed in Table 1.

Table 1 User stories

ID	Persona	As a [ROLE],	I want to [ACTION],	so that [BENEFIT]
1	Floor	decision-maker	know the appropriate size of air-conditioners for the AD Boog tents used during the Four Days Marches	I avoid complaints of the tents' occupants and event organizers
2			know if the tents rental company provides air-conditioning units appropriate for the provided tents	I can prevent discomfort in the tents
3			get reliable advice without having detailed information about the tents' properties and usage	the lack of information does not impair the system selection
4			Ensure that the indoor temperature specified in the program of requirements is achieved	I avoid complaints of the event organizers
5			adjust the air-conditioning capacity to the Dutch summer conditions	the system size matches the actual conditions
6			get advice for different types and sizes of tents	I can benefit from the tool in a few years when a different tents rental company will serve the event
7	Ben	decision-maker	avoid undersizing of the air-conditioners	I avoid complaints of the soldiers
8			avoid oversizing of the air-conditioners	soldiers' health is protected, energy is saved, and noise is avoided
9			size the HVAC indicating the desired indoor temperature range	I can adjust the indoor temperature to the local climate
10			understand what the risk of undersizing is	I can decide if the risk is acceptable
11			provide a system which is appropriate for the extremely hot climate	soldiers have comfortable or at least acceptable indoor conditions
12			be able to demonstrate to the soldiers the positive effect of shading installation in terms of thermal comfort and energy usage	I can convince the soldiers to install the shading cloths which are provided together with tents
13	Jasper	decision-maker	size the HVAC system indicating the time and location of the training	the capacity is adjusted to the season and location
14			use the detailed information that I have about the tent and its intended usage for the HVAC sizing	the advice is as accurate as possible
15	Jan	decision-maker	prove the soldiers that I did my best however it is impossible to achieve thermal comfort in tents in an extremely hot climate	the soldiers do not complain and blame me
16	Anne	purchase officer	know which HVAC systems are appropriate for newly bought tents and their typical applications	I can control and double-check the advice from tents' manufacturer
17			enter information about the tent's construction and size into the tool	I can use the tool for new tents of any construction

3.2 IDENTIFICATION OF REQUIREMENTS

The requirements specification techniques described in the subsection 3.1 helped to identify functional and non-functional requirements. The definition of a functional requirement is “any requirement which specifies what the system does”. Non-Functional requirements are defined as “any requirement which specifies how the system performs a certain function” (Eriksson, 2015). Functional requirements referring to user stories (Table 1) are listed in Table 2. Non-functional requirements identified for the decision support tool are listed in Table 3.

Table 2 Functional requirements

User stories ID	**Functional requirements**
1,2	The tool should work for tents currently used by the Ministry.
6, 16, 17	The tool should work for new tents of different geometry and construction.
3	The tool should include defaults which enable the user to use the tool without having detailed information about tents’ properties and usage.
14, 17	The tool should provide the possibility to enter detailed information about tents’ properties and usage when available.
5,11,13, 16	The tool should work for various climates.
4, 9	The tool should allow to adjust heating and cooling temperature setpoints.
7, 8	The tool should provide information about the peak cooling and heating demand.
7, 8 , 10	The tool should provide information about the effect of the application of an HVAC system of a smaller capacity than the peak demand.
13	The tool should filter the results by the time of the year.
15	The tool should demonstrate the effect of extreme climates on the thermal comfort in tents.
12	The tool should demonstrate the advantage of using shading in terms of thermal comfort and energy consumption.

Table 3 Non-functional requirements

Non-functional	
Waiting time	“Short” - < 1 min
Customizability	Configurable scenarios, tents geometries, and properties
Accuracy	Moderate uncertainty range suitable for sizing
Interoperability	Stand-alone tool or web-based tool
Accessibility	Distributed on individual PC or online restricted
Software	Not requiring installation of any software, running out of the box
Required prior knowledge of the user	Basic knowledge about intended application of the tent, its size, and basic properties
Attractive user interface	Minor importance

In essence, the DST is required to be user-friendly, flexible and reliable.

LOOK-UP TABLE AS A MEAN TO FACILITATE COMMUNICATION WITH THE CLIENT

In order to facilitate discussion with the client and to check if the client's requirements were understood correctly, in an earlier stage of the project, a look-up table for the representative scenarios of tents use was delivered to the client. A detailed description of the look-up table can be found in Appendix A, subsection 10.1. The look-up table is a pre-calculated database covering some common scenarios of tents use. The table is an Excel sheet with results filtering function and with hyperlinks to graphs. The look-up table was created for eight predefined tent types, whose specifications were provided by the client, considering four relevant locations. The look-up table covers in total 516,096 scenarios.

The client's feedback on the look-up table helped to establish the functionalities and features of the final DST. In general, the client had a good first impression. He liked the way the results are visualized by load duration curves and the possibility to adjust the HVAC system capacity to the season of the year. The client also appreciated thermal comfort indicators included in the output.

However, the client perceived the overall output as too extensive and confusing. Due to this, it was decided that in the final DST the output must be divided into two parts. One of them should contain only this piece of information that is necessary for the HVAC system sizing and the second one should contain additional information related to thermal comfort and energy demand. Moreover, the client wanted the DST to be more flexible. The DST should work for more climates and for user-defined tent's geometries and constructions. Moreover, it should provide the possibility to enter more detailed information about tents' properties and usage. The DST should also allow to freely adjust heating and cooling temperature setpoints.

In order to meet the requirements of the company advisor, the DST must cover a huge number of possible scenarios (or maybe infinite if the inputs could be freely defined by the user). Moreover, yearly time series data is necessary to generate similar outputs as in the look-up table. Based on this information, the decision about the final DST form was made.

4 DESIGN CHALLENGE

The DST is required to be user-friendly, flexible, and reliable. The desired features are explained in Table 4. Unfortunately, the features are conflicting with each other. For example, if a calculation tool is flexible and reliable, usually it is also complicated and requires much input information. If the tool is user-friendly and flexible, often it is also inaccurate because it must describe a complex system in a simplified way. If the calculation tool is user-friendly and reliable, it has also limited flexibility, because complex cases cannot be described in a simplified and accurate way at the same time. Therefore, the main challenge and aim of this project was to find the right balance between these three conflicting features (Figure 4).

The aim was realized on three levels. One of the levels is the tent simulation model development described in section 5. Another level is the decision on the DST form discussed in section 6 of this report. The third level is the design of the DST input and output described in subsections 7.2 and 7.3, respectively.

Table 4 Explanation of the DST desired features

User-friendly	- Intuitive for technically skilled users but not professionals in HVAC systems - Not requiring knowledge of programming languages - Not requiring installation of any software - User inputs limited to the information that is known to the user - Including default inputs - DST outputs not perceived as confusing by the user, providing necessary information
Flexible	- Covering a wide range of possible cases ○ Various locations ○ Various tent types ○ Various shading options ○ Various tent functions and required indoor temperature
Reliable	- Providing correct results - Providing information that allows the user to make informed decision

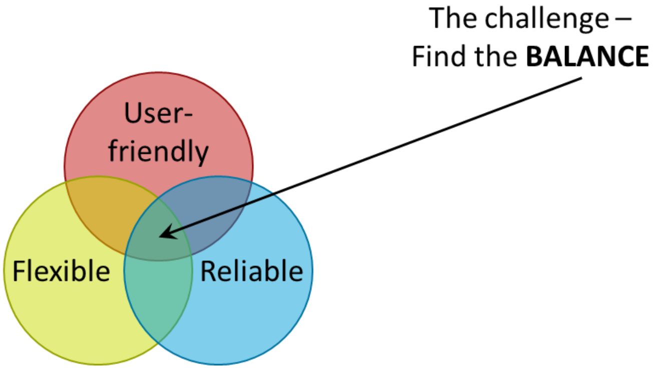


Figure 4 The desired features of the DST

5 DEVELOPMENT OF THE SIMULATION MODEL

5.1 LITERATURE REVIEW ON TENTS MODELING USING BPS

Building performance simulation (BPS) gives the opportunity to “build” a virtual building to predict what will happen in reality. The virtual building is a mathematical model created based on physical principles. The simulation accounts for the dynamic interactions between the building, occupants, installed equipment, weather conditions, and HVAC system.

A literature review on tents modeling using BPS was performed to learn how other researchers have approached thermal performance modeling of tents and what kind of challenges and difficulties they encountered. Nearly all of the studies that can be found in literature focus on refugee shelters that are not equipped with HVAC systems. Some of the reviewed studies are shortly discussed below.

(Fosas, Albadra, Natarajan, & Coley, 2018) proposed a cyclical process for improving refugee shelters by monitoring existing shelters, creating validated baseline simulation models of the shelters, and using these models for the shelter design optimization. Field studies were performed in a refugee camp in Jordan. Surface temperature, air temperature, and relative humidity were measured. Moreover, weather conditions were monitored. Also, camp residents were asked about their thermal sensation in the tents. The collected data was used to calibrate and validate EnergyPlus simulation models. The authors found it challenging to model the impact of the units surrounding the considered shelter. Also, the modeling of natural ventilation and infiltration was a challenge. The authors decided to model it using a single-zone airflow network. However, due to limitations in the field measurements, the authors had to apply optimistic guesses for the input data. Another challenge is the fact that despite all shelters are based on the same design and have a few design features, no two shelters are the same. A variability in ventilation, orientation, and thermal resistance of the construction was noted. To account for this variability, several model variants were employed. Another source of uncertainty is the fact that it is not possible to predict how interventions are used by occupants. Taking into account the between-shelter variability, uncertainties, and limitations, the created model was considered sufficiently accurate for the purpose of design optimization. The authors also studied thermal comfort in the shelters. They pointed out that the limits of discomfort and heat stress that are widely used can be only treated as a guess because they were developed based on healthy adults in very different climates. The authors also highlighted the significant impact of the surface temperature of the enclosing elements on thermal comfort. It was shown that shading and increased insulation level can contribute significantly to the improvement of thermal comfort while increasing thermal mass is not a very effective measure.

According to (Fosas, Moran, Natarajan, Orr, & Coley, 2019), BPS can help in improving thermal comfort in emergency shelters by forecasting shelter thermal performance as a part of the shelter design optimization process. Thermal performance of shelters in Jordan was measured and the results were used to evaluate uncalibrated EnergyPlus models, calibrated EnergyPlus models, on-site design variants, and off-site prototypes. The authors noted that it was unknown if BPS can make accurate predictions for a tent. The fact that the tents are built to unknown qualities together with the common uncertainties involved in BPS, make the simulation results particularly uncertain. Moreover, many parameters such as air-tightness or thermal resistance of the envelope are usually unknown. The authors considered the information regarding geometry, final operation, and weather as known for the model. The model template was based on information from the design specification and internal communication with the UNHCR organization. The tent was modeled as a single zone. The authors highlighted that the heat transfer with the ground is very important for shelters' thermal performance and they used the Kiva tool to model it. Natural ventilation was modeled with an airflow network. Due to the lack of data, the authors assumed a notional infiltration level. It was shown that uncalibrated models based on educated guesses and design documentation are sensitive to uncertainties but still useful. Nevertheless, model calibration improves model accuracy. Moreover, the model calibrated with data measured under determined weather conditions can be used also in different climatic regions.

(Obyn, van Moeseke, & Virgo, 2015) discuss the difficulties in achieving a realistic thermal model of a tent. The authors used EnergyPlus for the study. According to the authors, thermal modeling of tents is not obvious due to the following factors: skin fabric that is neither airtight not opaque, very low insulation level, very small thermal mass, major influence of the ground heat transfer, and interactions between the inner and outer skin. The authors divided the tent model into several zones connected by a resistive model and an airflow model. All surfaces were modeled as fully glazed to account for solar transmission. Only the floor was modeled as an opaque surface. The EnergyPlus models were calibrated and validated by comparing simulation results with measurements realized in Belgium, Burkina Faso, and Luxembourg. The parameters to be calibrated were the discharge coefficient used to model the infiltration and the soil thickness interacting with the shelter. The authors concluded that calibrated models are relevant and may reproduce the real thermal behavior of the shelter. However, the impact of the ground and the overcooling during the night in clear sky conditions are difficult to reproduce.

(Attia, 2014) measured temperature, humidity, and airspeed inside a Bedouin tent. A model of the tent was created using EnergyPlus and calibrated with the measurement data. According to the author, the main sources of uncertainty in the model are hygrothermal physical properties of construction materials, casual gains, infiltration rate, and impact of solar radiation. The tent was modeled as a single-zone. It was not perfectly sealed and idealized cracks were used to allow air leakage. The measurement data was used to calibrate the tent thermal properties and the infiltration rate.

(Cornaro, Sapori, Bucci, Pierro, & Giammanco, 2015) created an IDA ICE shelter model based on experimental data collected by the authors during short-term field measurements in Italy. The model was calibrated with the measurement data and further used to study the shelter improvement solutions. The authors made informed guesses of several input parameters because real values were not available. The infiltration was modeled as a fixed value. The authors claim that the advantage of modeling infiltration driven by wind is not significant.

(Crawford, Manfield, & McRobie, 2005) tested two tent types in laboratory conditions at a temperature of -20°C to characterize their thermal performance and to use the measurement results to calibrate an ESP-r model. The tent was modeled as two zones. The first zone was the tent itself, and the second represented the concrete floor. The modeled shelter was not perfectly sealed and idealized cracks were used to allow leakage and air exchange. The cracks areas were calibrated based on the measured air temperature in the tent. A significant variation of air temperature with height was observed during the measurements in the laboratory. However, in the ESP-r model, a simplified assumption of well-mixed conditions was applied.

To conclude, the information found in the literature regarding thermal modeling of tents is scarce and not very sharp. However, the authors agree that the most challenging aspects to be modeled are properties of construction materials, their light- and air-permeability, infiltration, interactions with the ground, and thermal stratification. Moreover, it was noted that most of the authors used EnergyPlus for the thermal modeling of tents. It was decided to apply EnergyPlus also for this project.

The researchers used field measurements to calibrate and validate their models. However, it must be noted that their focus lied on one specific tent type used for a specific function. For this project, the added-value of field measurements would be rather low and the effort considerable. The low added-value is caused by the fact that the DST, being the final goal of this project, is required to be generic and to work for user-defined tent types. Therefore, field measurements performed for one or even for a few tent types would not be valid for every tent type. Each tent has a different level of tightness and different ventilation options, is made of materials of different properties, has different construction of walls, roof, and floor, or even can be assembled more or less carefully. The thermal performance of a tent depends also on how long the door and the windows are open. For these reasons, it was decided to use uncalibrated models, based on informed and well-thought-out assumptions.

5.2 DEALING WITH MODELING CHALLENGES

The literature review helped to identify tents modeling challenges. An infographic presenting the challenges is shown in Figure 5. In this section (5.2), measures undertaken to overcome the challenges and to make certain decisions regarding the tent modeling approach are described. The goal was to come up with a model that has a satisfactory accuracy and does not require extensive, unavailable input information. Moreover, attention was paid to the fact that the modeling approach cannot use the worst-case assumptions for all aspects because although it would ensure low risk, it would often also result in substantial oversizing of the HVAC system. The oversizing is undesired for the reasons explained in section 1.1. Such a worst-case-based approach would question the usefulness of the DST.

Subsection 5.2.1 describes the typical materials military tents are made of and the HVAC systems commonly used in tents. A literature review concerning infiltration in tents is presented in subsection 5.2.2. In the next subsection (5.2.3), a literature review on thermal stratification is presented. Subsection 5.2.4 describes the investigation on ground modeling methods. The investigation on shading modeling is discussed in subsection 5.2.5. Subsection 5.2.6 describes the analysis of uncertainties.

The final decisions regarding the modeling approach are listed concisely in Appendix B, section 10.2.

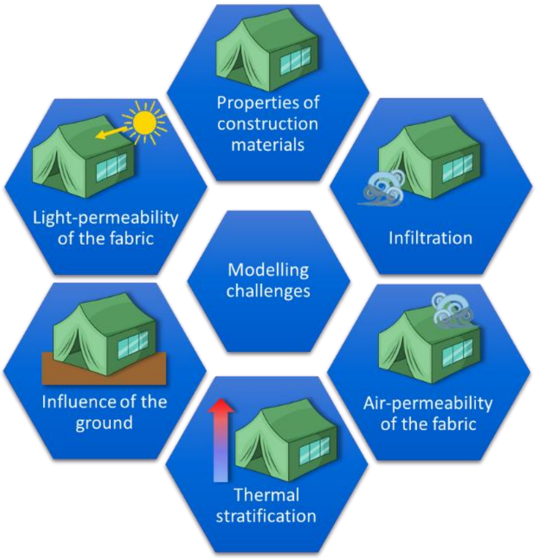


Figure 5 Modeling challenges

5.2.1 IDENTIFICATION OF TYPICAL MATERIALS AND HVAC SYSTEMS

According to the information collected from The Dutch Defense Organization, modern military tents are usually made of plastic fabrics, for example, PVC-coated PES fabrics. The fabrics can be both light-permeable and opaque. The tent envelope made of these fabrics can be either double or single-skin. Typical colors of military tents are dark green, white, and sand. No specific information about the air-permeability of the fabric is available. However, the impression of the people using tents made of PVC-coated PE fabric is that the material "does not breathe". Table 5 shows values of transmittance, absorptance, reflectance, and heat transfer coefficient. Values used in the final model can be found in Appendix B (section 10.2).

Table 5 Fabric properties

Property	Light colors	Medium colors	Dark colors	Information source
Transmittance	0.00-0.20	0.00-0.06	0.00-0.01	(Mehgies - Textiles to Transform, 2017), (Mehgies Mehler Texnologies, 2017)
Absorptance	0.04-0.15	0.22-0.55	0.85-0.90	
Reflectance	0.75-0.90	0.35-0.75	0.05-0.10	
U-value	5 W/m^{2}K			Communication with the tents manufacturer Schall

Military tents can be equipped with different kinds of floors, such as timber floor, PVC foil, insulated floor plates, concrete platform, or they can have no floor. Moreover, military tents' roofs can be shaded by sunscreens made of a plastic fabric or a net. Figure 6 presents black and white shading nets transmittance measured by (Abdel-Ghany, et al., 2019).

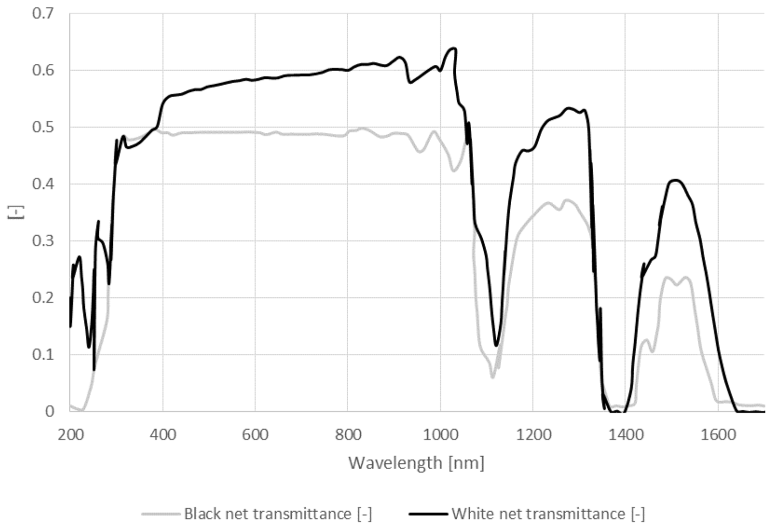


Figure 6 Shading nets spectral transmittance (Abdel-Ghany, et al., 2019)

Military tents are usually served by all-air HVAC systems controlled by thermostats installed inside. The heating and cooling energy is provided by mobile heaters and air-conditioners (examples can be seen in Figure 7 and Figure 8, respectively). The devices supply heated or cooled air to tents via air ducts. They can serve one or two tents at once. The supply air can be fully recirculated, fully fresh, or mixed. The mobile heaters are powered by diesel fuels. The mobile air-conditioners are powered by electricity from the grid or generated by diesel generators.

Figure 7 Mobile heater, Dantherm VA-M 40

Figure 8 Mobile air-conditioner, Dantherm AC-M7

5.2.2 LITERATURE REVIEW ON INFILTRATION IN TENTS

A literature review on air infiltration intensity was performed and the findings are listed in Table 6. Due to the lack of more detailed information, it was decided to model infiltration as a constant infiltration rate. Infiltration rate values used in the model can be found in Appendix B (section 10.2)

Table 6 Literature review on infiltration in tents - summary

Reference	Summary of the information about air infiltration	Type of tent
(Pilsworth, 1978)	Appropriate values of air infiltration (given in ACH) for tents are on the high side of those given typically for buildings. For fairly tight tents it is about 2 ACH. For unbanked tents, it is about 3 ACH. Under the worst conditions value of 5 ACH can be assumed.	Military tents
(Salvalai, Imperadori, Scaccabarozzi, & Pusceddu, 2015)	For a tent made of cotton and canvas (thin and permeable envelope) the value of 4 ACH was used. For a tent made of impermeable and waterproof polyester fabrics coupled with a multilayer insulator the value of 2 ACH was assumed. These parameters have been selected considering the results of wind tunnel testing.	Emergency shelter
(Manfield P. , Modelling of a Cold Climate Emergency Shelter Prototype and a Comparison with the United Nations Winter Tent, 2000)	For insulated tents covered by an impermeable plastic membrane which are very well sealed, in still air condition, the infiltration rate of 1.8 ACH was reported. Under similar external conditions, a tent made of cotton and canvas has a higher air change rate – the value of 4 ACH was assumed.	Emergency shelter
(Fosas, Moran, Natarajan, Orr, & Coley, 2019)	Likely infiltration bounds are established roughly between 0.5 and 2.5 ACH.	Emergency shelter
(Manfield P. , 2000)	The author assumed the value of 4 ACH for heat loss calculation performed for a polar expedition shelter, a yurt, and the UNHCR emergency shelter.	Emergency shelter
(Potangaroa, 2006)	The author listed figures for infiltration rates depending on pressure difference (50 or 5 Pa): Damp canvas – 45.6 $m^3/(hm^2)$ (50 Pa) 9.56 $m^3/(hm^2)$ (5 Pa) Dry canvas – 41.4 $m^3/(hm^2)$ (50 Pa) 13.3 $m^3/(hm^2)$ (5 Pa) Dry canvas with plastic liner– 32.6 $m^3/(hm^2)$ (50 Pa) 7.01 $m^3/(hm^2)$ (5 Pa) When the infiltration rates for the pressure difference of 5 Pa are recalculated to the ACH unit, the values are in the same order of magnitude as the infiltration rates indicated by other authors.	Emergency shelter

5.2.3 LITERATURE REVIEW ON THERMAL STRATIFICATION

Thermal stratification occurs often in buildings, particularly with large non-compartment volumes. Warm air rises due to buoyancy forces. Due to this, a positive vertical gradient between the building's floor and ceiling occurs. During winter, the layer of warm air below the ceiling increases heat losses through the roof and increases the stack effect which boosts air infiltration and exfiltration. Therefore, more heat is necessary to provide thermal comfort in the building. On the other hand, stratification may be beneficial and reduce cooling needs because the layer of warm air below the ceiling acts like an insulating buffer (Said, MacDonald, & Durrant, 1996).

Commonly used heating and cooling calculation methods are based on the mixed-air assumption. It means that air temperature and humidity are uniform throughout the zone. For some HVAC systems and building typologies, the assumption is valid (Schiavon, Lee, Bauman, & Webster, 2011). However, in buildings where significant thermal stratification occurs, the mixed-air assumption may lead to improper design of the HVAC system.

Information about the thermal performance of military tents can hardly be found in the literature. Authors who studied the thermal performance of emergency shelters (Poschl, 2016), (Manfield P. , 2000), (Crawford, Manfield, & McRobie, 2005), (Battilana, 2001), (Flanders, 1981), (Attia, 2014) highlight the presence of thermal stratification and its significant impact on the thermal comfort. However, the emergency shelters studied by the authors differ from military tents. The most important difference in terms of thermal performance is that emergency shelters are not equipped with HVAC systems. Sometimes there are convective heaters installed in the shelters, however, forced air heating and cooling systems are never used. The forced air systems have a significant effect on the airflow and temperature distribution in tents. Due to this, a literature survey was performed on thermal stratification in large industrial halls or warehouses which are relatively high, have large volumes, and no internal partitions similarly as military tents.

THERMAL STRATIFICATION IN INDUSTRIAL HALLS AND WAREHOUSES AND ITS RELATION WITH HVAC SYSTEMS

According to the REHVA guideline on energy-efficient heating and ventilation of large halls (Kabele, Hojer, Kotrbaty, Sommer, & Petras, 2011), due to the thermal stratification effect, warm air heating is not suitable for spaces higher than 6-7 m. For heat loss calculations, the authors recommend using a vertical temperature gradient of 0.8-1.0 K/m. If the air circulation rate is significant, the temperature gradient of 0.4-0.5 K/m can be used. However, the values of temperature gradient are given for the situation when the supply-air diffusers are mounted on the upper part of the wall and there is no exhaust ventilation. Therefore, the values cannot be used for military tents to which supply and return air ducts are connected usually directly above the floor. According to the authors of the REHVA guideline, the vertical temperature gradient decreases with an increase in air circulation. This is also confirmed by (Przydrozny & Szczesniak, 2013).

ISSO publication 57E (Instituut voor Studie en Stimulering van Onderzoek op het Gebied van Gebouwinstallaties, 2006) provides a method for the calculation of the heat loss for tall spaces. The calculation method is similar to the method provided by standard (NEN-EN 12831

, 2004) but it contains some extensions taking into account the thermal stratification effect. The publication provides a guideline for calculating various correction factors for temperature gradients which are used for the calculation of transmission heat losses, ventilation heat losses, and infiltration heat losses. The guideline is given for four heating systems: radiators, heating panels, floor heating, and warm air heating. There is only one configuration of the warm air heating considered – exhaust diffusers mounted on the wall close to the ceiling and supply diffusers localized on the wall slightly lower than the exhaust diffusers.

(Kurnitski, Ahmed, Simson, & Sistonen, 2016) investigated the differences in temperature distribution in two hall buildings about 10 m high – one building had an air heating system and another one a radiant ceiling panel heating. The authors measured the vertical temperature gradient in winter. The results showed a gradient of 0.2 K/m for both buildings. For the case of air heating, the temperature distribution is sensitive to the outdoor temperature and has a more fluctuating character. The results of the study cannot be directly used for the case of military tents because in the building with air heating, in contrast to the military tents, the air is supplied from the upper part of the walls. Moreover, the hall buildings are well insulated, and military tents are not.

(Szczesniak, Przydrozny, Pelech, & Walaszczyk, 2014) studied the temperature distribution in an 8 m high unventilated and unheated industrial hall where large process heat gains are generated. The authors performed field measurements of the temperature distribution. The mean temperature gradient was 0.5 K/m. The authors observed that outdoor air temperature influences the absolute value of air temperature in the hall however the gradient of 0.5 K/m remains the same. On the other hand, the value of temperature gradient changes drastically when the amount of process heat gains changes.

(Porras-Amores, Mazarron, & Canas, 2014) monitored temperature distribution in five warehouses with different building typology and height. One of them is equipped with an air-conditioning system and the rest is not. In the warehouse with the air-conditioning, both temperature and humidity are controlled by fan-coil units and humidifiers. The devices are located close to the ceiling. The authors observed that there is a strong impact of the outdoor temperature on the indoor temperature gradient. During summer, the ceiling and upper zone get warmer and cold air is accumulated in the lower zone. During winter, the ceiling gets cold and the colder air moves down and due to this, vertical temperature differences are very small. The presented results show that in the case of the air-conditioned warehouse, during the cooling season the thermal stratification effect is negligible. The cool air pushed from the fan-coil unit located close to the ceiling moves down and homogenizes the air temperature. During the heating season, the thermal stratification is more noticeable. The warm air pushed from the fan-coil unit accumulates in the highest zone causing temperature gradient up to 0.9 K/m. The authors concluded that air-conditioning helps to maintain the homogeneity of the indoor temperature and limits the influence of the outdoor temperature on the stratification.

(Said, MacDonald, & Durrant, 1996) measured thermal stratification in eight aircraft hangars during the heating season. Half of them were equipped with vertical discharge forced warm air heating systems and half of them were heated by downdraft convective unit heaters. The authors observed that outdoor temperature variation seems to have a small impact on thermal stratification. Also, the ceiling height and roof shape are not contributing factors. Most of the vertical temperature change occurs in the working zone. The authors concluded that thermal stratification may have a big influence on the building's heating needs.

(Karpuk, Pelech, Przydrozny, Walaszczyk, & Szczesniak, 2017) performed measurements of air temperature distribution in high industrial halls with mixing ventilation system under significant sensible heat load conditions. The supply air was delivered downwards to the occupied zone. The exhaust grill was located under the ceiling. The authors distinguish two zones in the building – occupied zone and transitional zone. The operating zone should be provided with the requested level of air temperature due to thermal comfort or technological expectations. In the transitional zone existing above the occupied zone, thermal comfort does not need to be achieved, and stratification and higher temperature can occur. The authors observed that the temperature gradient in the transitional zone decreases with increasing distance from the operating zone. Significant temperature growth appears within 2 m distance from the operating zone.

(Li, 2016) investigated the thermal stratification effect in warehouses during the heating season. Field measurements were performed in five warehouses differing in shape, placement of different items, and heating and cooling system. Four of the warehouses showed temperature stratification. The temperature difference was in the range from 2.7 K to 20.6 K. It was observed that thermal stratification varied significantly depending on the applied heating system. Both heaters type and number of heat distributors affected the thermal stratification. Another factor influencing the indoor air temperature distribution is the building geometry. The cooling from the roof reduces the thermal stratification. The author studied also the effect of mechanical mixing of indoor air with fans using CFD simulation. It was concluded that mixing fans can reduce the temperature in the zone close to the ceiling and increase the temperature in the occupied zone. Moreover, mixing fans can reduce heating energy needs. Furthermore, CFD simulation results showed that setting diffusers to supply air downwards in a warehouse reduces thermal stratification more efficiently in comparison to other airflow directions.

COOLING LOAD CALCULATIONS FOR STRATIFIED AIR DISTRIBUTION SYSTEMS

The main objective of this review is to find out the implications of thermal stratification on the HVAC system sizing approach. To get a better understanding of the impact of thermal stratification on the cooling loads, a literature review on stratified air distribution systems was performed.

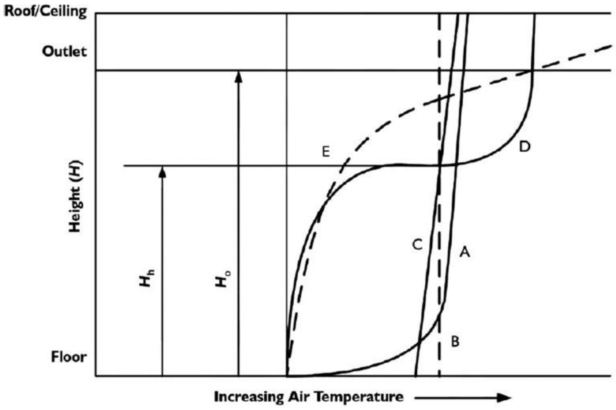
(Hui & Yichun, 2015) performed a study concerning underfloor air distribution systems (UFAD). The authors highlight that application of UFAD systems is still limited by the lack of knowledge of how to calculate cooling loads. UFAD systems create partly mixed room conditions that vary between two extremes – fully mixed and thermal displacement. The UFAD system creates unique temperature profiles. There are three zones in the room representing air diffusion – lower mixed zone, middle stratified zone, and upper mixed zone. The profile can vary significantly due to various control factors, room height, the momentum of supply air, and the design of air inlets and outlets. To benefit from the thermal stratification, the UFAD system should be designed in such a way to exclude a portion of heat gains when calculating space cooling load. The cooling load reduction is mostly influenced by the vertical location of the inlets and outlets, and the split of the radiant and convective components of the heat sources. For cooling load calculations, space is divided vertically into two zones – occupied zone and unoccupied zone. The UFAD system is designed to provide thermal comfort in the occupied zone only. During cooling load calculations, only those convective heat gains which are captured within the occupied zone should be considered. Moreover, for the cooling load calculations, all the transmission and infiltration heat gains that occur above the occupied zone can be neglected. The authors concluded that thermal stratification, management of solar and lighting loads, architectural design, and thermal properties of the structural floor slab influence the cooling load and must be analyzed with caution.

According to (Hongtao, Naiping, & Jianlei, 2009), thermal stratification provides energy-saving possibilities. For stratified air distribution systems, a part of heat gains can be excluded from cooling load calculations. The reduction of the cooling load of a heat source depends on its vertical location and radiant and convective split. There are several options for the inlets and outlets placing: 1. Floor supply, floor return, and exhaust, 2. Floor supply, ceiling return, and exhaust, 3. Floor supply, floor return, ceiling exhaust, 4. Floor supply, middle return, ceiling exhaust. Option 1 is the least common however it is used in military tents. For this configuration, two airflow patterns are possible. The temperature in the occupied zone may be stratified or uniform, depending on the thermal length scale of the floor supply jets. If the ratio of the thermal length scale of the floor supply jets to the room height is >>1, the temperature gradient is minor and the air is well-mixed. If the thermal length scale of the supply jets is small, strong stratification exists close to the floor.

(Cheng, et al., 2018) reviewed several cooling load calculation methods focused on stratified air distribution systems (STRAD). The authors also developed a database of effective cooling load factors using CFD simulations. STRAD systems provide supply air directly to the occupants and cool the lower occupied zone leaving the upper zone uncooled. In the article, two types of STRAD systems were considered – displacement ventilation and underfloor air distribution system. In both cases, the air is supplied from the floor level upwards and the return and exhaust grilles are located under the ceiling. According to the authors, only the space heat gains that are released within the occupied zone need to be included in the cooling load calculation. If only the occupied zone is cooled and the upper zone is not, cooling energy can be reduced. The occupied zone is usually considered as the lowest 1.8 m of the room. Several authors proposed methods of cooling load calculation considering only the occupied zone. According to (Chen & Glicksman, 2003) the effective cooling load for displacement ventilation in an office room can be calculated as the sum of the heat generated by the occupants, desk lamps and equipment, heat generated by the overhead lighting, and conduction heat through the room envelope, and the transmitted solar radiation heat gains multiplied by weighting factors for different space heat sources which are defined as the fractions of the cooling loads entering the space between the head and the feet of a sedentary occupant. For UFAD systems, according to (Loudermilk, 1999), space should be split into a mixing occupied zone and displacement upper zone. For cooling load calculation, entire radiant heat gain should be considered and convective heat gain originated out of the occupied zone should be excluded from calculations. A similar approach of space separation into the occupied and unoccupied zone was proposed by (Bauman, Webster, & Benedek, 2007). However, the applicability of the existing methods is limited to the tested conditions and predefined locations of return and exhaust grilles (Cheng, et al., 2018).

IMPACT OF HEATING SYSTEM ON THERMAL STRATIFICATION

There is a limited number of publications discussing the impact of heating on thermal stratification. According to (Andersen, 1998), in heated spaces, temperature stratification depends on how heat is supplied and how fresh air is mixed. Typical stratifications are presented in Figure 9. Line A corresponds to the situation when the heat is supplied close to the floor level. It can be noted that significant stratification occurs under the heating air inlet. On the other hand, above the heat supply, the stratification effect is very small.



A: Heat supplied evenly and close to floor level.
B: Heat supplied evenly in the space and air is well mixed.
C: Heat is supplied evenly in the room with little air mixing.
D: Heat is supplied from ceiling or upper part of walls with little air mixing.
E: Heat is from a concentrated source in the upper part of the space with little air mixing after.

Figure 9 Vertical temperature distributions in heated rooms

(Flanders, 1981) studied the performance of an air-transportable shelter in a cold climate. The shelter was an insulated container heated by a fan-coil space heater standing on the floor. The author reported that field measurements showed no thermal stratification and no cold spots in the container.

CONCLUSION

To conclude, thermal stratification in buildings is a complex phenomenon that depends on many factors, for example, presence and type of HVAC system, placement of supply and return-air grilles, ventilation rate, air-mixing, building typology, insulation level, outdoor temperature, and internal heat gains. Existing literature is mostly focused on HVAC systems which are commonly used in buildings - mixed air systems with inlets and outlets close to the ceiling, displacement ventilation, or underfloor air distribution systems with inlets in the floor and outlets under the ceiling (or on the upper part of walls). In the case of military tents, both inlets and outlets are usually connected to the bottom part of the tent’s walls, therefore the airflow is completely different than for the aforementioned systems. In order to accurately predict the airflow, CFD simulation must be performed, however, it is out of the scope of this project. The physical phenomenon that is governing thermal stratification is buoyancy which moves warm air up and cold air down due to the density difference. If the warm air is supplied to a tent from the bottom part, it rises to the ceiling level, cools down because of conduction through the roof, and moves down. Therefore the temperature distribution is rather complex and the presence of exhaust openings in the bottom part makes it even more complicated. Therefore, the best possible approach for heating load calculation is the mixed-air assumption which is also supported by (Flanders, 1981) and (Andersen, 1998) who claim that if the heat is supplied close to the floor level, the stratification effect is small. Due to the lack of unambiguous information about which modeling approach is the best to calculate cooling loads, the mixed-air model is used, as the most conservative approach.

5.2.4 INVESTIGATION ON GROUND MODELING

Compared to conventional buildings, military tents have a large contact area with the ground in relation to their volume, and they are often built with an uninsulated floor. Various studies have shown that ground heat transfer plays an important role in the heat balance of tents and therefore the way the ground coupling is modeled has a big impact on the simulation results (Obyn, van Moeseke, & Virgo, 2015), (Poschl, 2016), (Pilsworth, 1978), (Manfield, Ashmore, & Corsellis, Design of humanitarian tents for use in cold climates, 2004). However, there is no guidance about how the ground coupling should be modeled for tents. Due to this, various methods of ground modeling available in EnergyPlus were analyzed and a multi-criteria analysis was used to support the decision-making on which method should be used. Multi-criteria decision methods facilitate and formalize the decision-making process. It is especially useful when the objectives are conflicting with each other. The method improves the quality of decisions by making them more explicit, traceable, rational, and efficient.

Multi-criteria analysis is composed of the following steps (San Cristobal Mateo, 2012):

Step 1: Defining the problem, generating alternatives and evaluation criteria
Step 2. Assigning criteria weights
Step 3. Construction of the evaluation matrix
Step 4. Selecting the appropriate method
Step 5. Ranking the alternatives

According to (Kirkels, 2018), the last (6th) step is sensitivity analysis. By the analysis, it is checked if the ranking can be impacted by the uncertainty of data or changes in the weighting factors.

STEP 1: DEFINING THE PROBLEM, GENERATING ALTERNATIVES AND EVALUATION CRITERIA

There are a few ways of ground-coupling modeling in EnergyPlus. These methods differ in complexity, the amount of input data required, and the degree of the reality simplification. The objective of this analysis is to analyze the methods of ground modeling available in EnergyPlus and to make the decision on which approach should be used for the project.

There are five alternative solutions. The first one is to include no model representing ground heat transfer. The second approach is to simply use ground temperatures taken from weather data for a given location (further called the simple method). The third solution is to use the Slab Preprocessor program integrated with EnergyPlus simulation. The fourth option is to use the Site:GroundDomain:Slab EnergyPlus object. The fifth approach is to apply the Kiva tool coupled with EnergyPlus simulation.

The following evaluation criteria were defined:

- Robustness
  Robustness is the quality of being unlikely to break or fail (Oxford, 2020). In this context, robustness is the ability of the model to work for all considered scenarios and boundary conditions. The model must be universal – the same model must work for all locations by changing only the model's boundary conditions (weather data). This is very important because the DST must be reliable but also flexible.
- Simulation time – The DST is required to be fast. Therefore, a short simulation time is an important factor.
- Abstraction error – All models suffer from an abstraction error because by definition, a model is a simplified representation of reality. The higher model complexity, the lower abstraction error, as can be seen in Figure 10.
- Input uncertainty – Input uncertainty is the uncertainty of input data required by a model. The more complex the model, the more input is required. The aim is to find a fit-for-purpose ground-coupling model. The fit-for-purpose model complexity is represented by the orange line in Figure 10. There is a trade-off between the input data uncertainty and the abstraction error. The lowest overall error is achieved when the input uncertainty and the abstraction error are in balance.
- Numerical error – Numerical errors are related to converting mathematical models into a form that can be addressed through computational analysis.

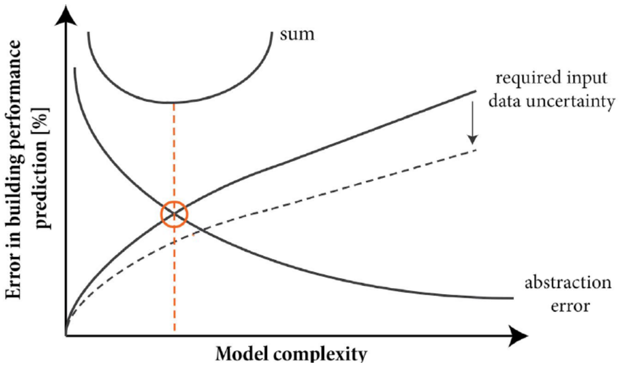


Figure 10 Model complexity vs. prediction error (van Enk, 2016)

The DST must work for locations spread over the whole world. Accurate identification of ground types for all the locations would be difficult or maybe impossible. Moreover, ground properties are strongly influenced by the moisture content which is impossible to predict. Therefore, the potential input uncertainty related to ground properties is high. Due to this, it is difficult to decide which ground modeling approach should be chosen for the project.

AVAILABLE GROUND MODELING METHODS

No information about ground (Nothing)

If no information about ground temperature and properties is included in the simulation file, the program assumes a constant ground surface temperature of 13°C. This temperature interacts with the surfaces and zones adjacent to the ground. The ground surface temperature influences the ground heat transfer and floor temperature. However, the ground temperature is considered as undisturbed – it means that the building does not influence the ground surface temperature.

Simple method

The most simple method of ground coupling modeling is to assign ground-contact surfaces to the “Ground” outside boundary conditions and to enter the monthly average ground surface temperature to the Site:GroundTemperature:BuildingSurface object. (Ringold, 2016) However, it is problematic to define ground surface temperature. Weather files contain monthly average ground temperatures at the depths of 0.5, 2, and 4 meters so there is no information about the ground surface temperature. Moreover, the available ground temperatures are calculated in an approximate way as a sine wave with amplitude and lag based on the annual dry-bulb air temperature profile and the depth below the surface, with the soil diffusivity held constant. Because of the simplified temperature input, the magnitude of the ground heat transfer might be over- or under-predicted. However, the simple method requires no data about ground properties.

Slab preprocessor

The next method is the application of the EnergyPlus auxiliary program called Slab Preprocessor. Now the preprocessor is also integrated into EnergyPlus however still the ground heat transfer calculations are decoupled from the thermal zone calculation. The program performs 3D ground heat transfer calculations and calculates monthly average temperatures of the core and the perimeter of the interface between the building surfaces and the ground. (big ladder SOFTWARE, 2019) It also produces the average based on the perimeter and core areas used in the calculation. The calculated ground surface temperatures can be used as the input to EnergyPlus using the OtherSideCoefficients object or the GroundTemperatures object. Separate monthly average indoor air temperatures are the input to the slab program. (big ladder SOFTWARE, 2019)

The calculated ground surface temperatures are considered as disturbed what means that they are influenced by the seasonal heat flux in and out of the ground. However, there are certain limitations. The ground heat transfer is calculated using monthly averaged indoor temperature setpoints which must be entered manually. The variation of the indoor air temperature can be modeled only by using a single value of a daily sine wave variation amplitude for the whole year.

Site:GroundDomain:Slab object

Another method is to apply the Site:GroundDomain:Slab object in EnergyPlus. The principle is the same as the preprocessor- the temperature of the interface between ground and building surface is calculated. The ground heat transfer calculations are 3-dimensional. However, in contrast to the preprocessor, the calculations are integrated into the EnergyPlus timestep and the interface temperature is calculated for each time step (instead of monthly average). The second difference between the preprocessor and the Site:GroundDomain:Slab is that the GroundDomain method uses an undisturbed ground temperature model (Costa, Roriz, & Chvatal, 2017). It means that the impact of the building on the ground temperature is not taken into account. The calculations are coupled to the EnergyPlus heat balance by applying a boundary condition to EnergyPlus 1D conduction. (Kruis, 2019) The ground domain must interact with the zone through an OthersideConditionsModel as the horizontal surface outside boundary condition. (U.S. Department of Energy, 2018) This method also requires extensive input regarding soil and slab properties.

Kiva foundation tool

Kiva is a ground heat transfer calculation tool that is now integrated into EnergyPlus (Big Ladder Software, 2019). Kiva performs 2-dimensional ground heat transfer calculations. Each foundation is represented by a single floor and a single wall. Individual walls are mapped to a single representative wall. Kiva uses boundary conditions from weather data, solar position, zone temperatures from the previous timestep, and zone radiation to calculate the convective heat gains and surface temperatures of the floor and the wall. The calculations do not use the same algorithm as the rest of the simulation. Kiva instances are initialized independently from the rest of the simulation using the accelerated initialization method. This method looks back in the weather file and simulates long timestep (on the order of weeks or months) calculations using an implicit numerical scheme. The initialization of the ground relies on assumptions of indoor air temperatures (thermostat setpoint or 22°). (U.S. Department of Energy, 2018)

TESTING OF GROUND MODELING METHODS

The ground modeling methods can be evaluated on abstraction error and input uncertainty criteria based on the methods' description. To evaluate them on the robustness, simulation time, and numerical error criteria, it is necessary to perform numerical experiments.

In order to do this, a model of the tent shown in Figure 11 was created. The dimensions of the tent are 12 x 30 x 5 m (W x L x H) and sidewall height is 3 m. The envelope is made of a PVC coated fabric. The tent has no floor. The lack of floor was modeled as a 2 cm layer of soil. Rocky laterite soil was assumed and its properties are presented in Table 7. There are no internal gains and no heating and cooling limits. The heating setpoint is 15°C and the cooling setpoint is 30°C. Infiltration rate of 2 ACH was assumed (Pilsworth, 1978), (Manfield P. , Modelling of a Cold Climate Emergency Shelter Prototype and a Comparison with the United Nations Winter Tent, 2000), (Salvalai, Imperadori, Scaccabarozzi, & Pusceddu, 2015).

Figure 11 Operating tent

Table 7 Laterite soil properties

Conductivity [W/(mK)]	0.499
Density [kg/m^3]	1630
Specific heat [J/kgK]	1104
Moisture content [%]	5.9
Moisture content at saturation [%]	43

Five models were created differing in the ground modeling approach. The simulations were run using weather files for three locations – Burkina Faso (extremely hot climate, only cooling is necessary), Italy (intermediate climate, both cooling and heating is necessary), and North

Canada (extremely cold climate, only heating is necessary). The variants are visualized in Figure 12.

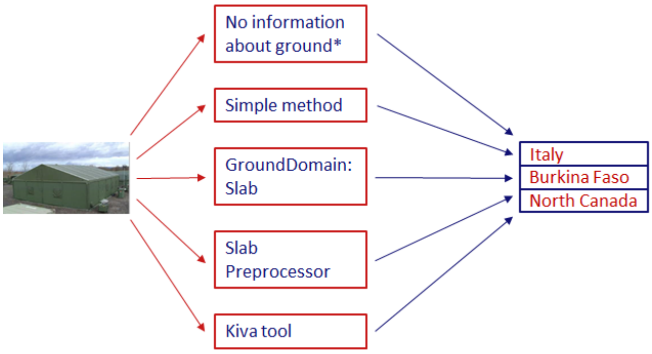


Figure 12 Modeling variants *EnergyPlus assumes ground-floor interface surface temperature of 13°C

Running the simulations allows evaluating the simulation time and the robustness criteria directly. The simulation times for the five modeling alternatives are listed in Table 8. When it comes to the robustness, all models work for all climates (extremely hot, intermediate, and extremely cold) with one exception – the Slab Preprocessor does not work for the extremely cold climate. Therefore, the robustness of the Slab Preprocessor is evaluated negatively while the remaining models' robustness is evaluated positively as can be seen in Table 8.

It is much more challenging to identify numerical errors. To do that, simulation results were analyzed. It was checked if the results are in line with common sense, the models' assumptions, and the governing physical phenomena. For all five modeling alternatives, cooling loads, heating loads, and floor temperature were investigated. Additionally, for the disturbed (taking into account the impact of building on the ground temperature) ground coupling models – Slab Preprocessor and Kiva, ground heat transfer was analyzed.

Figure 13 presents cooling load duration curves and peak cooling loads calculated using the five ground modeling approaches for the climates of Italy and Burkina Faso. There are significant discrepancies between the results obtained using different ground modeling methods. It shows that the investigation of the ground modeling methods applicability is very relevant. For both climates, the highest cooling demand is calculated using the GroundDomain:Slab method. The lowest values were calculated assuming the constant ground surface temperature of 13°C ("Nothing" label on the graphs). Using the "nothing" method, the lowest cooling demand was calculated because the ground surface temperature of 13°C is lower than both the outdoor air temperature and the cooling setpoint temperature. Due to this, the ground acts as a heat sink. The situation is similar when using the simple method which assumes that the ground surface temperature is equal to the ground temperature at the depth of 0.5 m from the weather file. In summer, the ground surface temperature is higher than the ground temperature at greater depths (Popiel & Wojtkowiak, 2013). Therefore, when applying the 0.5 m depth temperature as the surface temperature, the surface temperature is lower than the cooling setpoint temperature and again the ground acts as a heat sink. Using the Kiva tool and the Slab Preprocessor, intermediate values of the cooling demand are calculated. These two methods calculate the disturbed ground temperature. It means that the ground affects the indoor temperature but also the indoor temperature affects the ground. The peak cooling demands calculated using different ground modeling methods differ from each other. However, the order of magnitude (tens of kilowatts) is similar – there are no outliners.

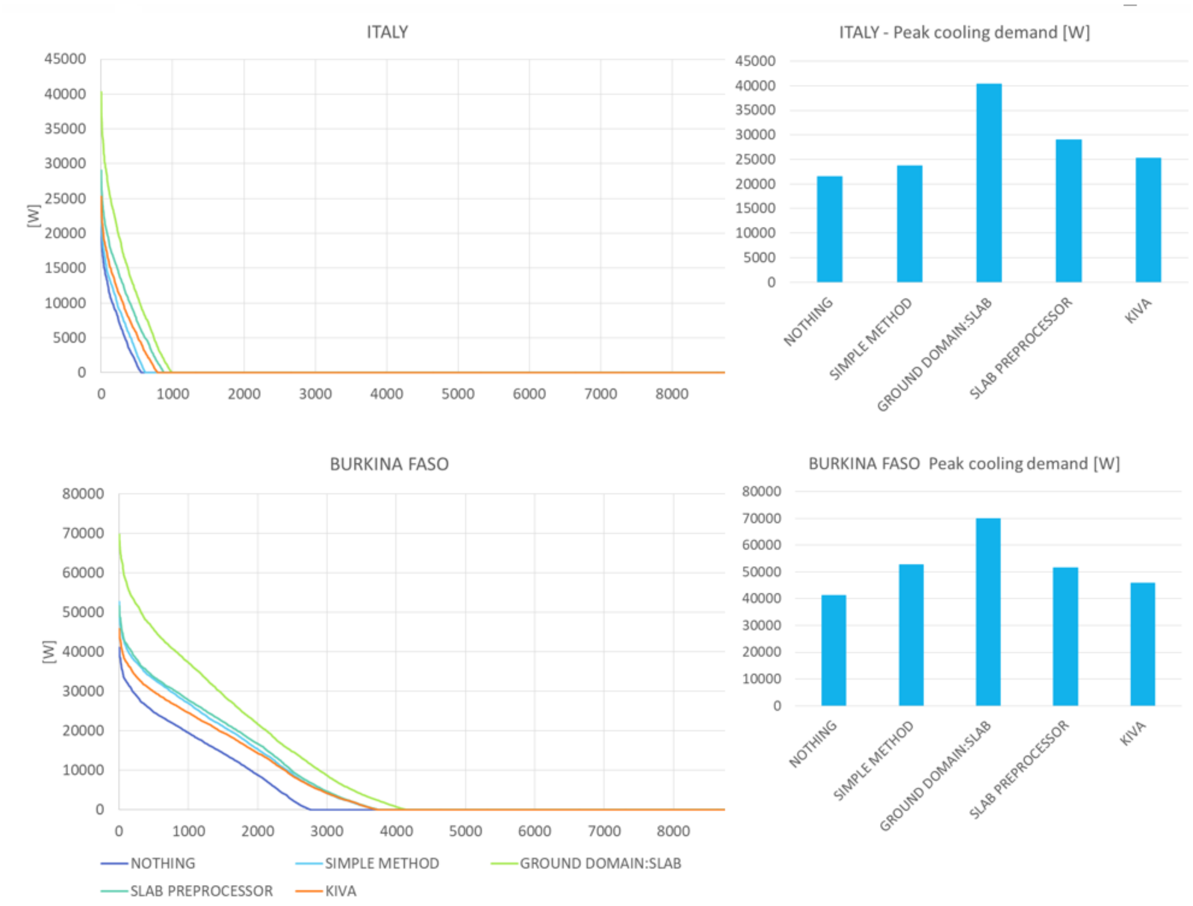


Figure 13 Cooling load duration curves and peak cooling demands calculated using the five ground modeling approaches for the climates of Italy and Burkina Faso

Figure 14 shows the heating load duration curves and peak heating demands calculated using the five ground modeling approaches for the climates of Italy and North Canada. There are large discrepancies between heating loads calculated using the five ground modeling methods. The highest heating demand is calculated by the simple method. The reason is that the ground surface temperatures equal to the ground temperatures at the depth of 0.5 m from the weather files are very low for heating load calculation under a heated tent. The second high heating loads were calculated by the GroundDomain:Slab method. The lowest heating loads were calculated again by the “nothing” method and Kiva tool. The constant ground surface temperature of 13°C assumed by the “nothing” method is high in comparison to winter outdoor temperature. For the location of Italy, the Slab Preprocessor shows intermediate heating loads. For the location of North Canada, the Slab Preprocessor shows an error. Again, despite the discrepancies, the order of magnitude of the heating loads calculated using different ground models is the same (tens of kilowatts).

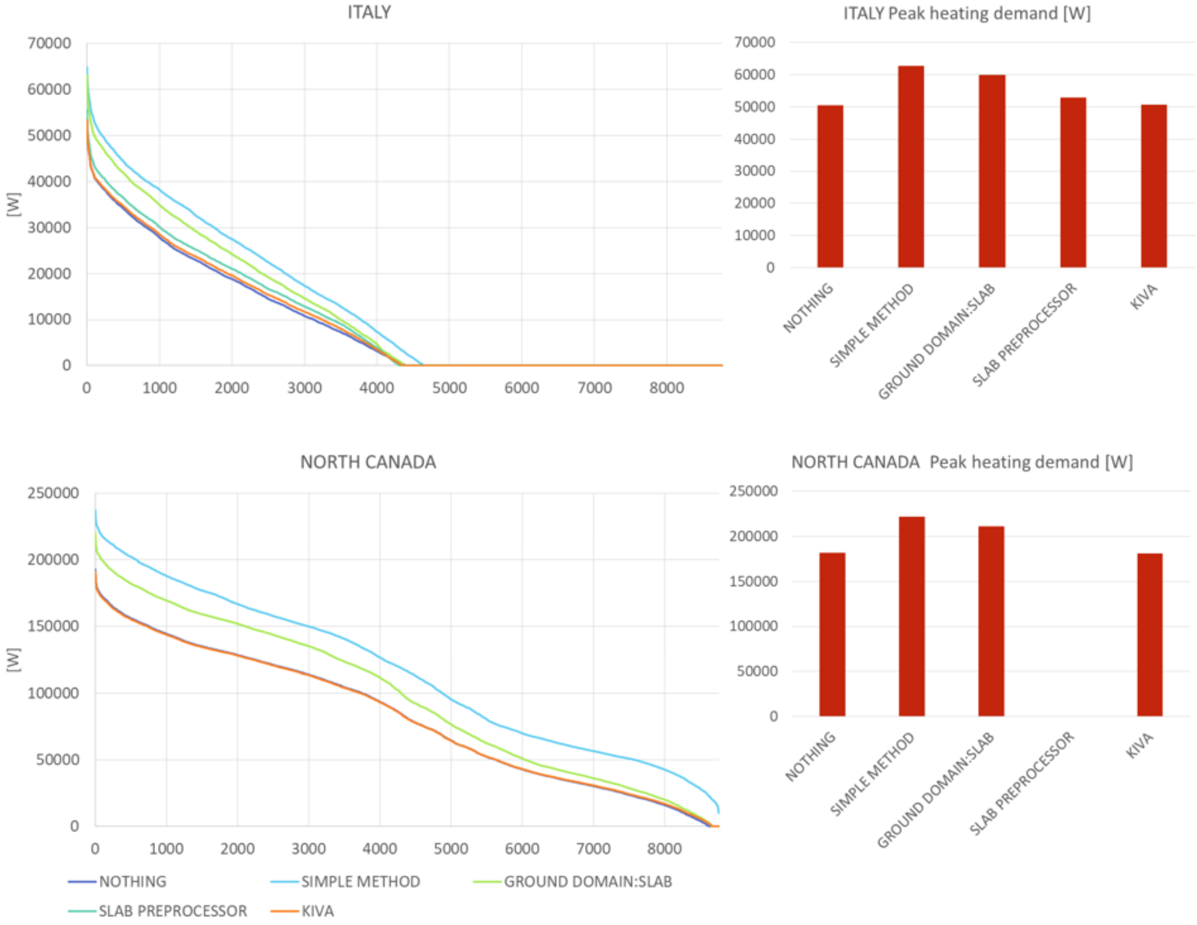


Figure 14 Heating load duration curves and peak heating demands calculated using the five ground modeling approaches for the climates of Italy and North Canada

Figure 15 presents the floor surface temperature calculated using the five ground modeling approaches for the three analyzed locations during a winter week and a summer week. Additionally, the air temperature was also plotted for comparison. The results per model are discussed in the paragraphs below Figure 15.

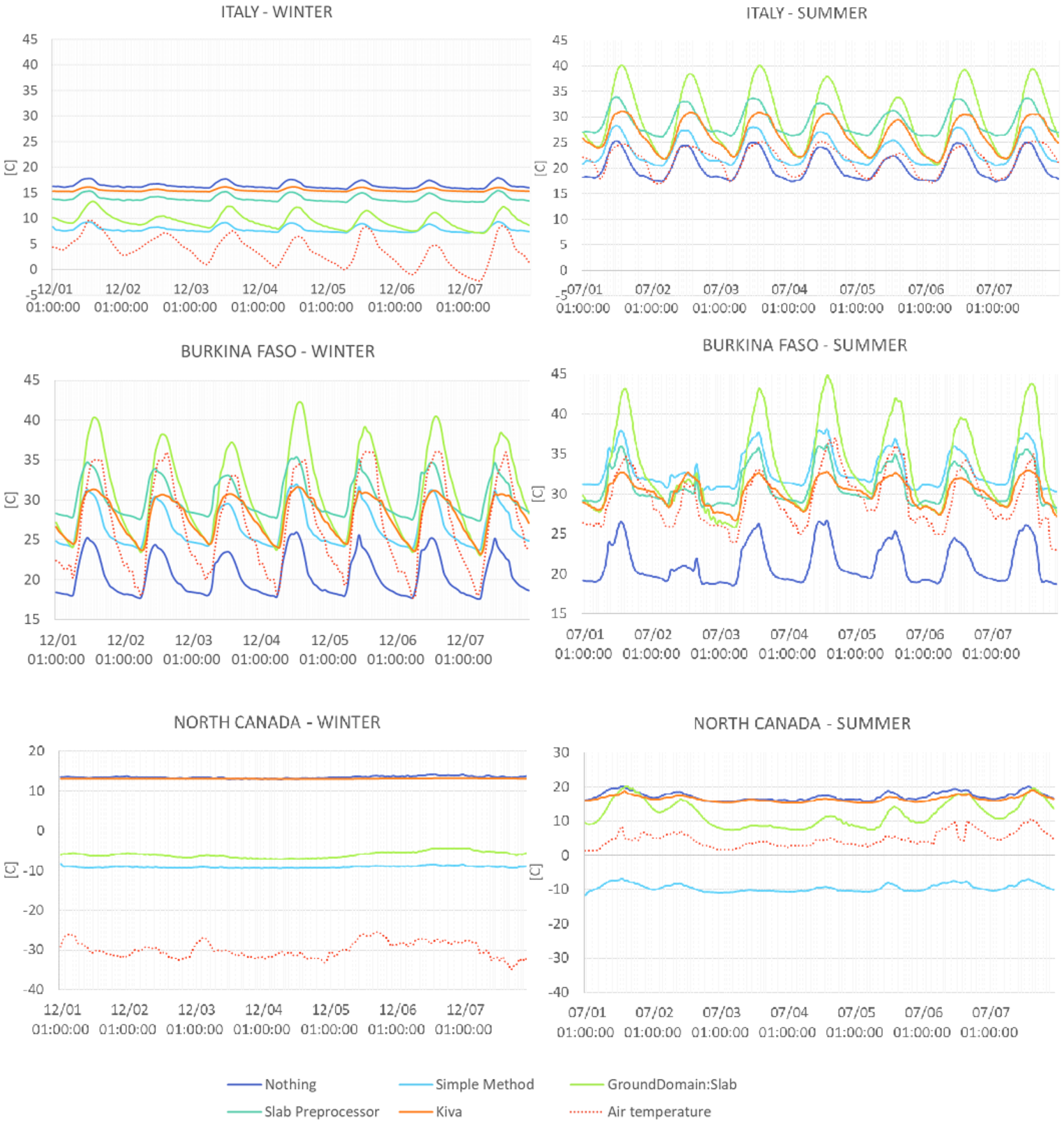


Figure 15 Floor surface temperature calculated using the five ground modeling approaches

No information about ground (Nothing)

If no input regarding ground is included in the simulation file, EnergyPlus assumes the constant and undisturbed ground surface temperature of 13°C regardless of location, climate, season, and the presence of the building. This temperature is too high for cold climates which is visible in the graphs for North Canada in Figure 15. In winter the floor temperature is more than 40 K higher than the outdoor air temperature. It must be noted that the presence of the heated tent and its impact on the ground surface temperature is not considered. Kiva shows similar floor surface temperature however this is a result of the heating setpoint of 15°C. The ground surface temperature of 13°C is also too low for hot climates what can be seen in the graphs for Burkina Faso in Figure 15. During summer days, the floor temperature is about 20

K lower than the air temperature and during summer nights about 10 K lower. In intermediate climates, the temperature of 13°C is much higher than the outdoor air temperature in winter. This approach does not follow the governing physical phenomena. However, the results are in line with the method's assumptions.

Simple method

The simple method applies the monthly ground temperatures at the depth of 0.5 m from the weather file as the ground surface temperatures. The ground temperatures in the weather file are calculated in an approximate way as a sine wave with amplitude and lag based on the annual dry-bulb air temperature profile. Again, the temperatures are undisturbed by the air-conditioned tent. According to (U.S. Department of Energy, 2018), these temperatures are too extreme for heating and cooling load calculations. Although these temperatures are not recommended for load calculations, this method is the only one that does not require extensive data related to soil properties. The floor temperatures shown in Figure 15 are in line with expectations considering the assumptions of the simple ground modeling method.

Site:GroundDomain:Slab object

The GroundDomain:Slab method calculates the temperature of the interface between ground and building surface. This method applies undisturbed ground temperature models. It means that the impact of the building on the ground temperature is not taken into account. Therefore, the calculated surface temperature depends only on the weather conditions. Because of that, for climates where intensive solar radiation occurs, the interface surface temperature is highly overestimated, which is confirmed by the tent floor temperature in Burkina Faso and in the summer in Italy. The tent floor temperature achieves 40-45°C. On the other hand, during winter in North Canada, there is no solar radiation and the calculated floor temperature of a heated tent equals about -7°C. Figure 16 shows examples of the relation between the floor temperature calculated using the GroundDomain: Slab method and solar radiation. The floor temperature follows the trends of solar radiation. Taking into account that the fabric transmittance of 0.1 was assumed and that the indoor air temperature is kept in the range between 15 and 30°C, this behavior is not realistic. However, this is a result of the model assumption – the ground is undisturbed by the building.

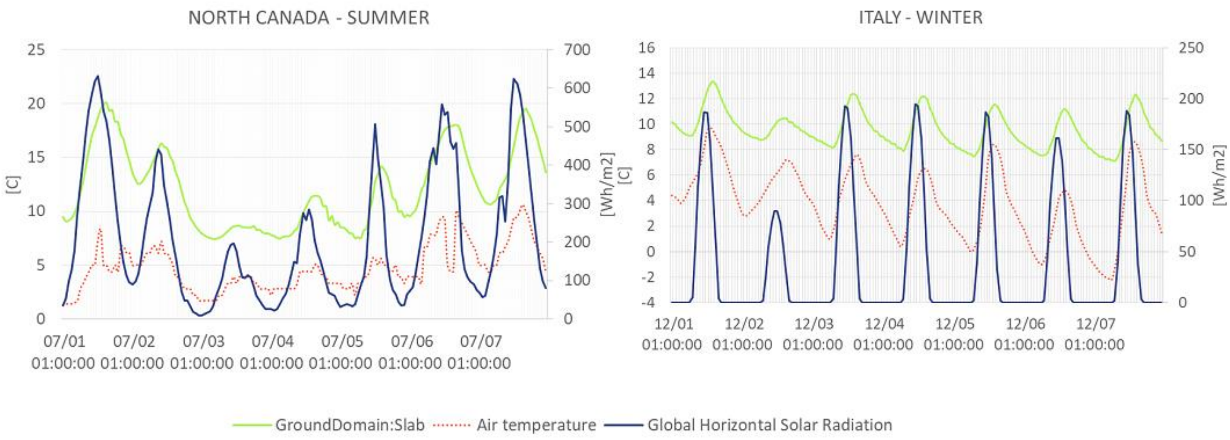


Figure 16 Floor surface temperature calculated using the GroundDomain:Slab approach in relation to the solar radiation

Kiva foundation tool

Kiva uses boundary conditions from weather data, solar position, zone temperatures from the previous timestep, and zone radiation. Figure 15 shows that for Italy and Burkina Faso, the floor surface temperature calculated using Kiva fluctuates around the setpoint temperatures. During the day, the floor temperature is slightly higher than the setpoint temperature and during night lower. During the cooling season, at night the indoor air temperature is lower than the cooling setpoint and due to this, the floor temperature drops. In North Canada during winter, the constant indoor temperature of 15°C is held because the heating is always on. Moreover, there is no solar radiation. Therefore, the calculated floor temperature is almost constant and equal to 13°C. During summer, very slight fluctuations of the floor temperature occur which are caused by solar radiation. Moreover, the floor temperature is slightly higher than the heating setpoint temperature (about 15.5°C). Figure 17 shows the comparison of the floor temperature when the heating is on and off. If the heating system is off, the floor temperature is close to the outdoor temperature as expected. Kiva provides results that are in accordance with expectations.

Slab preprocessor

The Slab preprocessor gives similar floor temperature patterns as the Kiva tool. However, higher temperatures are achieved during the cooling season and lower temperatures are achieved during the cooling season. This is caused by the fact that the preprocessor considers the indoor air temperature to be either equal to 30°C (cooling setpoint) or 15°C (heating setpoint). Because of that, the floor does not have the chance to cool down during the night when the indoor temperature is below 30°C. The temperature step between the heating setpoint and the cooling setpoint is large - 15 K. Figure 18 presents the effect of this temperature step on the floor surface temperature. Between the heating season and the cooling season, there is a sudden increase in the floor temperature. Although these sudden temperature changes are not realistic, they result from the Slab Preprocessor assumptions.

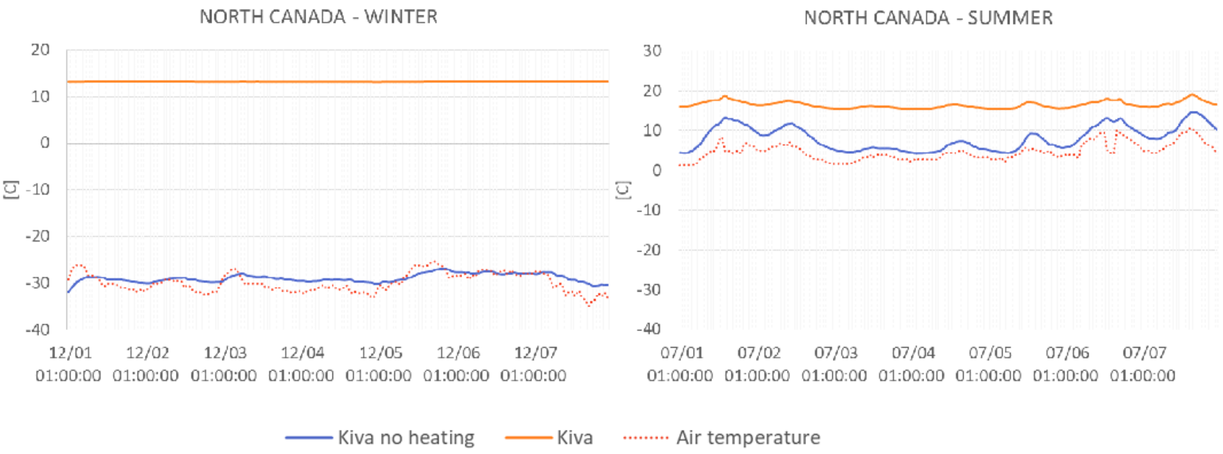


Figure 17 Comparison of floor temperature when the heating is on and off (Kiva)

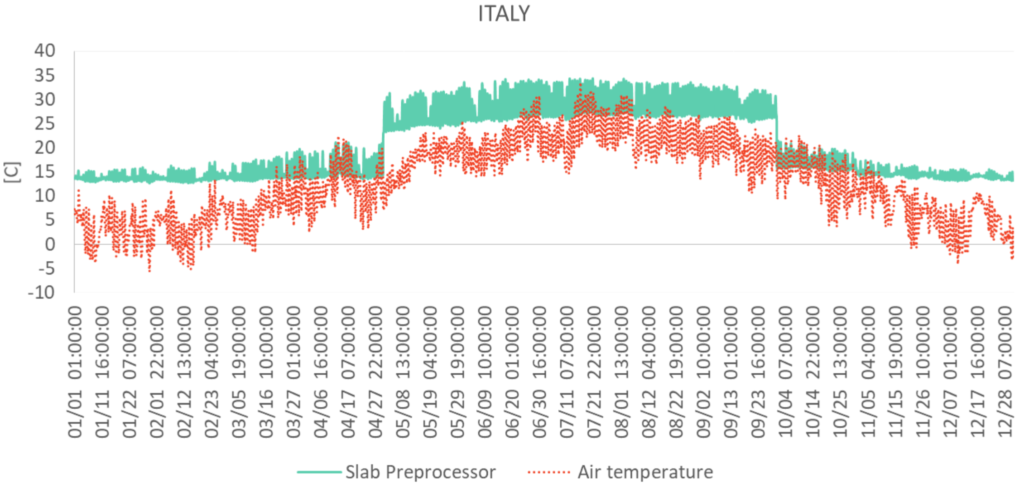


Figure 18 Floor surface temperature calculated using the slab preprocessor for the climate of Italy

For the disturbed ground coupling models (Slab Preprocessor and Kiva), an analysis of heat transfer through the floor was performed. In order to analyze the ground heat transfer, 1 m of floor insulation was added to the models, and results were compared with the base case (no floor and no insulation). The results are discussed and summarized below.

Kiva

As can be seen in Figure 19, for the three analyzed climates, the heating and cooling loads calculated using the Kiva tool do not change significantly when the 1 m layer of insulation material is added to the floor. This behavior is unexpected. To investigate the reason for that, the heat transfer through the floor was calculated and plotted in Figure 20. The addition of the 1 m thick insulation should decrease the heat transfer through the floor to about 0. Moreover, it should significantly moderate fluctuations. However, Figure 20 shows that the 1 m floor insulation has a relatively small impact on the heat transfer through the floor.

In order to confirm that these unrealistic results are not caused by a man-made error, a similar test was done using the ZoneCoupledKivaSlab.idf example model from the EnergyPlus package. The example model was created by the Kiva tool developer and therefore it is assumed to be reliable. The model was simulated in its initial form (0.0254 m of floor insulation) and after the addition of 1 m thick floor insulation. The obtained load duration curves are shown in Figure 21. The additional insulation has almost no impact on the cooling load. On the other hand, it has a large influence on the heating load. When the floor is better insulated, the heating load is lower, as expected. Figure 22 presents the heat transfer through the floor for the cases with 0.0254 m and 1 m of insulation. During summer, the additional 1 m of insulation has almost no impact on the floor heat transfer and therefore, it has also almost no impact on the cooling load. In winter, the additional floor insulation causes heat gains instead of reducing heat transfer through the floor, which is not physically possible. The reduction of heating load (which is visible in Figure 21) is an effect of the heat gains from the floor. The analysis of the ground heat transfer uncovered a numerical error in the Kiva model.

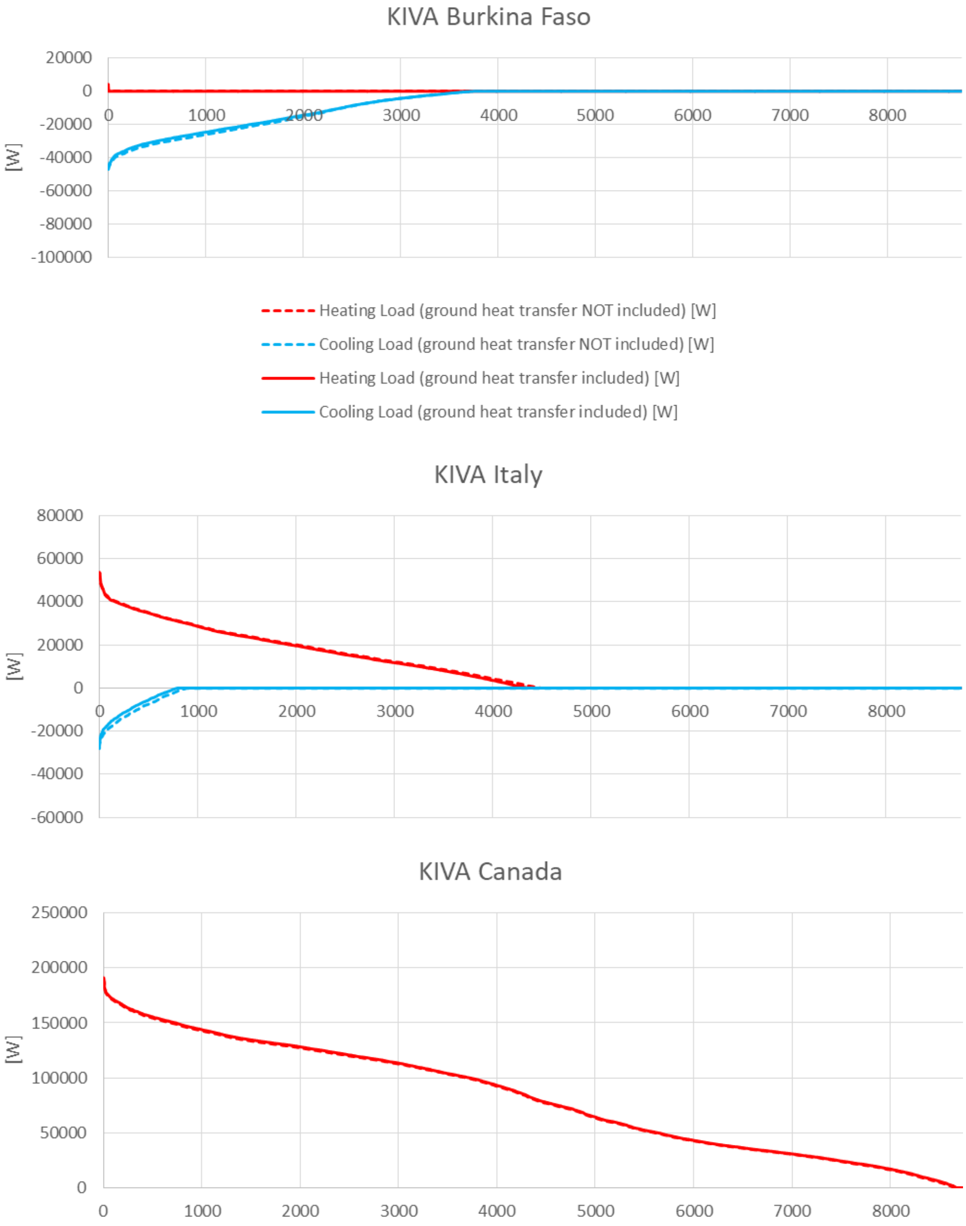


Figure 19 Load duration curves calculated using the Kiva ground modeling method

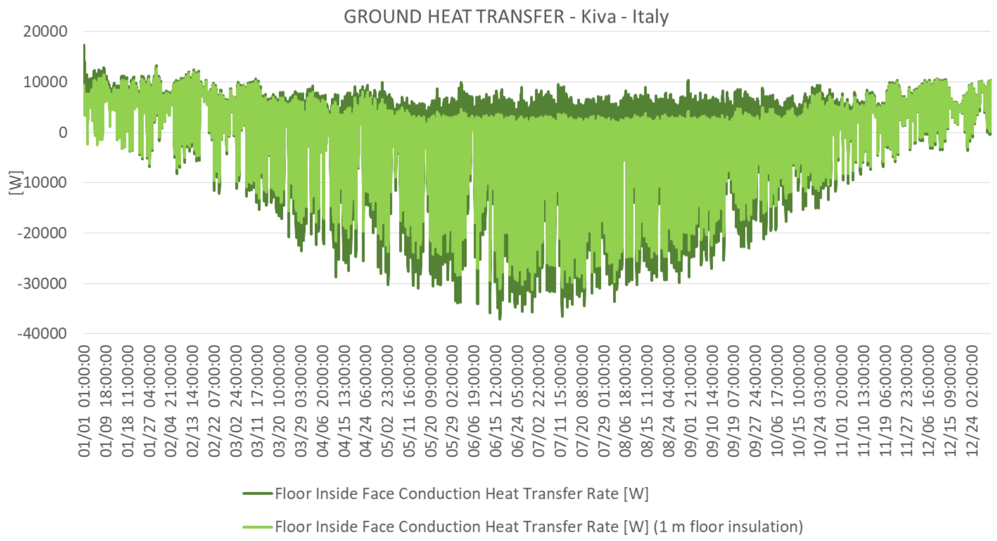


Figure 20 Ground heat transfer calculated using the Kiva ground modeling method with no floor insulation and with 1m of floor insulation

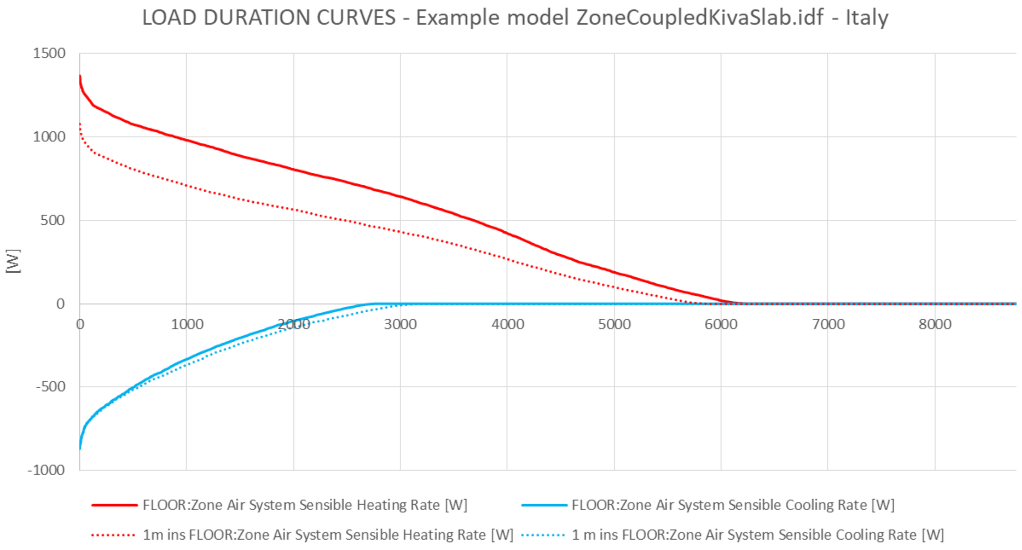


Figure 21 Load duration curves calculated for EnergyPlus example model ZoneCoupledKivaSlab.idf with default floor insulation level (0.0254m) and with 1m of floor insulation

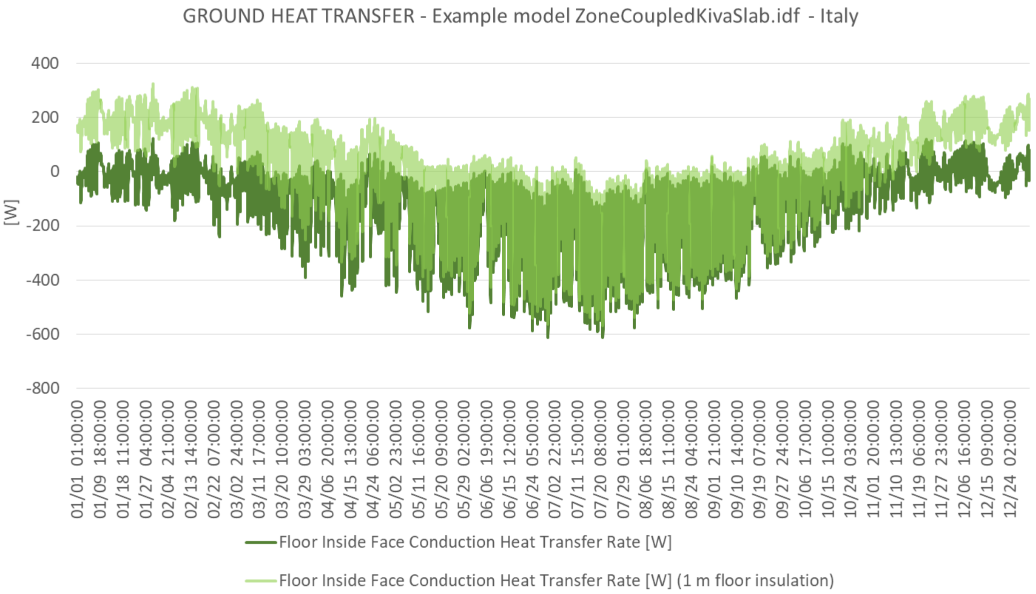


Figure 22 Ground heat transfer calculated for EnergyPlus example model ZoneCoupledKivaSlab.idf with default floor insulation level (0.0254m) and with 1m of floor insulation

Slab preprocessor

Figure 23 presents the load duration curves calculated using the Slab Preprocessor. For Burkina Faso, when the ground heat transfer is excluded from the calculations, a higher cooling load is calculated and during a few hours per year, heating is needed. In Italy, when the ground heat transfer is omitted, the cooling load is higher as well. The omission of the ground heat transfer results in a slightly higher heating load. This is caused by the reduction of heat gains from the ground which is visible in Figure 24 showing heat transfer through the ground. When 1 m thick insulation is added to the floor, the heat transfer through the ground gets nearer to zero, as expected.

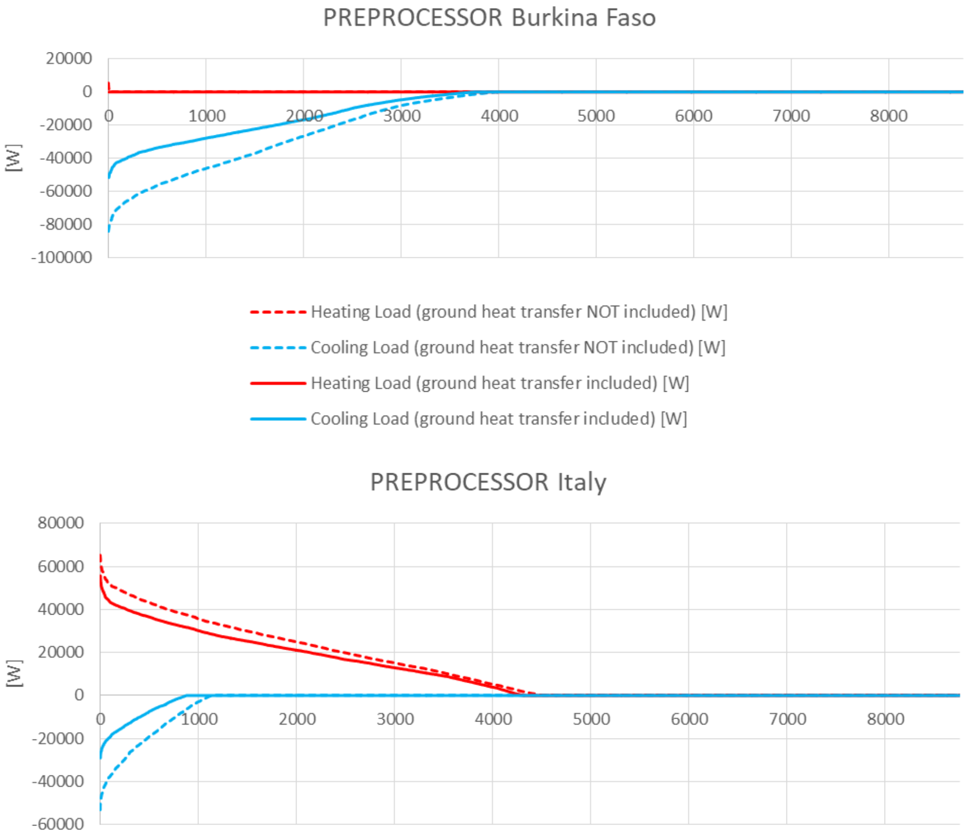


Figure 23 Load duration curves calculated using the Slab Preprocessor

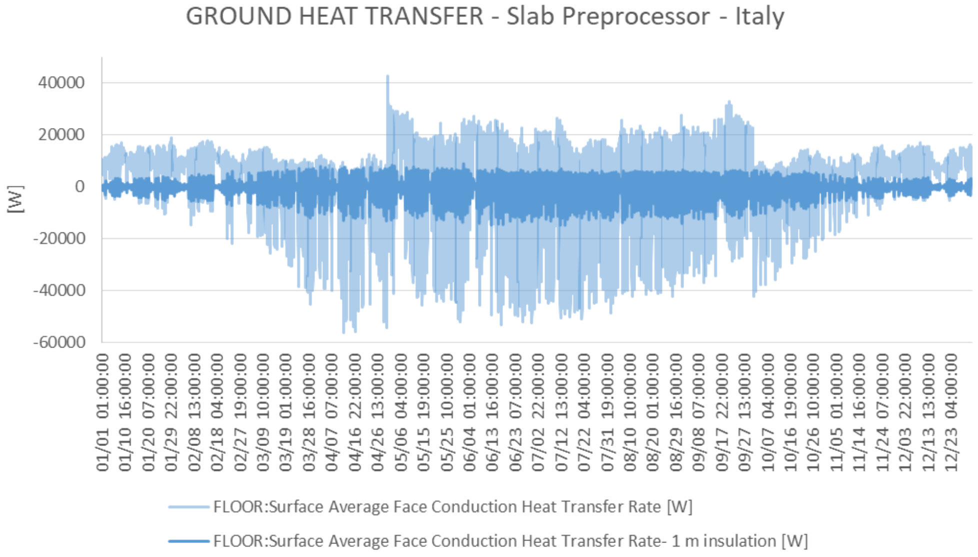


Figure 24 Ground heat transfer calculated using the Slab Preprocessor with no floor insulation and with 1m of floor insulation

To sum up, none of the ground modeling methods is perfect. The analysis allowed identifying the strengths and weaknesses of each method. In the next step, the multi-criteria analysis was performed to support the decision on which ground modeling method should be used in this project.

EVALUATION OF THE GROUND MODELING METHODS ALTERNATIVES ON THE ESTABLISHED CRITERIA AND WEIGHTING FACTORS SETTING

After information about the ground modeling methods was collected and their strengths and weaknesses were identified, the methods could be evaluated on the established criteria. Table 8 shows the evaluation matrix. The +/- column indicates the direction of the criteria. A '+' means that a higher score is positive, a '-' indicates that a higher score is negative. Most of the evaluation criteria are qualitative. The only quantitative criterion is simulation time measured in seconds.

Table 9 shows the criteria grading description.

To make the importance of the criteria explicit, weighting factors are assigned. The weighting factors were assigned based on subjective opinion built on previous experiences, knowledge, and interviews with the client. The most important criteria are robustness, numerical error and input uncertainty for the following reasons:

- Robustness – The model must be reliable. The DST user cannot experience any problems with the calculation procedure.
- Numerical error – If a numerical error exists, even if the method's assumptions are proper, the calculations give incorrect results.
- Input uncertainty – The DST must work for every location that the user specifies. The ground properties of the specified location are not known both for the DSR developer and the DSR user. Therefore, the DST cannot require extensive data about ground properties.

Another criterion is the abstraction error that describes how imperfect the representation of reality in the model is.

Simulation time also needs to be taken into account because the DST user cannot accept too long waiting time.

Because the established criteria are both qualitative and quantitative, the mixed data MCA method proposed by (Voogd, 1982) and explained by (Kirkels, 2018) will be used for this assignment.

Table 8 Evaluation matrix

Options / Criteria	No information about the ground in the tent model	Simple method	GroundDomain: Slab	Slab Preprocessor	Kiva tool	+/-	[dimension]	Weight-ing factor
Robust-ness	0	0	0	+	0	-	qualitative	25
Simulation time	5	5	444	23	6	-	[seconds]	10
Abstrac-tion error	+++++	+++	++	+	++	-	qualitative	15
Numerical error	0	0	0	0	+	-	qualitative	25
Input uncer-tainty	+	+	+++	++++	+++	-	qualitative	25
							SUM	100

Table 9 Criteria grading description

Criteria	Grading description
Robustness	0 – robust – simulation always work + - not robust – simulation crashes in at least one case
Simulation time	Duration of the simulation in seconds
Abstraction error	+++++ - Very high abstraction ++++ - High abstraction +++ - Intermediate abstraction ++ - Low abstraction + - Very low abstraction
Numerical error	+ – Numerical error identified 0 - Numerical error not identified
Input uncertainty	++++ - Very high input uncertainty +++ - High input uncertainty ++ - Intermediate input uncertainty + - Low input uncertainty

The next step was to calculate the dominance scores. The dominance scores are calculated separately for quantitative and qualitative criteria. Qualitative criteria indicate not only which alternative is better but also how much better. It is worth to use this information. To make various criteria comparable, it is necessary to standardize the quantitative data. The standardized quantitative data are listed in Table 10. After standardization, the quantitative dominance scores can be calculated. The dominance score of one option indicates the extent to which the option is better or worse than another option. If the dominance score is positive, it means that the considered alternative scores better than the other alternative (which we compare the considered alternative with). On the other hand, if the dominance score is negative, it means that the considered alternative scores worse than the other alternative. The quantitative dominance scores are listed in Table 11.

Table 10 Standardized quantitative scores

Options Criteria	No information about the ground in the tent model	Simple method	GroundDomain:Slab	Slab Preprocessor	Kiva tool	[dimension]	Weighting factor
Simulation time	1.000	1.000	0.000	0.959	0.998	[seconds]	10

Table 11 Quantitative dominance scores

	No information about the ground in the tent model	Simple method	GroundDomain:Slab	Slab Preprocessor	Kiva tool
No information about the ground in the tent model		0.00	10.00	0.41	0.02
Simple method	0.00		10.00	0.41	0.02
GroundDomain:Slab	-10.00	-10.00		-9.59	-9.98
Slab Preprocessor	-0.41	-0.41	9.59		-0.39
Kiva tool	-0.02	-0.02	9.98	0.39	

No standardization is necessary for qualitative data. The plusses indicate scoring on an ordinal scale that is representing the order. Therefore, the plusses do not represent how much one option is better than another. For qualitative criteria, dominance scores are calculated as well. The qualitative dominance scores are listed in Table 12.

Table 12 Qualitative dominance scores

	No information about the ground in the tent model	Simple method	GroundDomain:Slab	Slab Preprocessor	Kiva tool
No information about the ground in the tent model		-15.00	10.00	35.00	35.00
Simple method	15.00		10.00	35.00	35.00
GroundDomain:Slab	-10.00	-10.00		35.00	25.00
Slab Preprocessor	-35.00	-35.00	-35.00		-10.00
Kiva tool	-35.00	-35.00	-25.00	10.00	

After quantitative and qualitative dominance scores were calculated, they could be combined into overall dominance scores. The overall dominance scores matrix is the final result of the MCA calculations.

Table 13 presents the overall dominance scores. The last column shows the ground modeling methods ranking. The first place is achieved by the simple method because all overall scores of this method are positive. The method assuming no input information about the ground in the model is in the second place. The advantage of these two methods is their simplicity, robustness, and low input uncertainty. The GroundDomain:Slab is in third place because it is robust, has intermediate abstraction error, however, the input uncertainty is high. Moreover, the simulation time is very long. The last two places are taken by the Kiva tool and the Slab Preprocessor. The Kiva tool has a numerical error and the Slab Preprocessor is not robust. These two criteria are very crucial therefore they influenced the MCA analysis results significantly.

Table 13 Overall dominance scores

	No information about ground in the tent model	Simple method	GroundDomain:Slab	Slab Preprocessor	Kiva tool	Ranking
No information about ground in the tent model		-2.76	3.06	6.48	6.43	2
Simple method	2.76		3.06	6.48	6.43	1
GroundDomain:Slab	-3.06	-3.06		5.25	3.37	3
Slab Preprocessor	-6.48	-6.48	-5.25		-1.88	5
Kiva tool	-6.43	-6.43	-3.37	1.88		4

An important part of the multi-criteria analysis is sensitivity analysis. The sensitivity analysis allows making sure that the final ranking might not be impacted by the uncertainty of data, small changes in weighting factors, or different interests of different actors. It checks the solidness of the conclusion of the MCA (Kirkels, 2018). The sensitivity analysis is described in detail in Appendix C, section 10.3. The analysis proved that the ranking presented in Table 13 is stable.

CONCLUSION

The MCA results showed that the Simple Method applying the ground temperatures from weather data as ground surface temperatures is the best approach. This was confirmed by the performed sensitivity analysis presented in Appendix C, section 10.3.

5.2.5 INVESTIGATION ON SHADING MODELING

Military missions often occur in hot climates. To decrease tent cooling energy consumption, to reduce the required capacity of air-conditioners and to increase thermal comfort, it is recommended to use shading. Shading is a passive strategy that reduces solar heat gains. The market offers many types of shading materials that can be used with tents. Shadings screens can be made of different kinds of fabrics, for example, open nets or closed plastic fabrics. Moreover, vegetal mats are sometimes used in emergency situations. They can provide similar shading factors as synthetic materials however they weigh more, have a shorter lifespan, and are not fire retardant (De Vilder, Buyle, & Virgo, 2015). Therefore, they are not appropriate for military tents and they are not considered in this analysis.

The goal of this analysis is to define the shading modeling approach and to identify the impact of the shading material properties on the tent heating and cooling needs.

PLASTIC SUN-SHIELDS

Military tents can be shaded by plastic fabric sun-shields. Figure 25 presents an example of a military tent equipped with such a sun-shield. The sun-shields are often made of PVC coated PES fabric. The fabric is not air-permeable. Nevertheless, it permits some solar radiation. The amount of solar radiation being permitted depends on the fabric properties. The properties are dependent on the fabric structure, composition, thickness, and color. Figure 26 shows that the incident solar radiation is partly transmitted by the fabric, partly reflected and partly absorbed. Due to the fact that the fabric is not air-permeable and that the distance between the tent roof and the sun-shield is relatively small (usually 10-20 cm), the air-cavity is not well ventilated. The absorption of solar radiation causes an increase in the cavity air temperature. The cavity heat is then transmitted through the tent roof to the inside air and causes an indoor air temperature rise. Therefore, it is beneficial to use light-colored plastic sun-shields (characterized by high reflectance and low absorptance). It is also recommended to increase the distance between the roof and the sun-shield to enhance the ventilation of the cavity. Moreover, it is recommended to make ventilation openings at the top of the sun-shield to allow the hot cavity air to be removed by convection.

Figure 25 Plastic fabric sun-shield (Schall, 2020)

RECOMMENDATION

It is recommended to:

- use light-colored plastic sun-screens (high reflectance and low absorptance)
- increase the distance between the sun-shield and the roof to enhance ventilation
- make ventilation openings at the top of the sun-shield to enhance convective air-flow

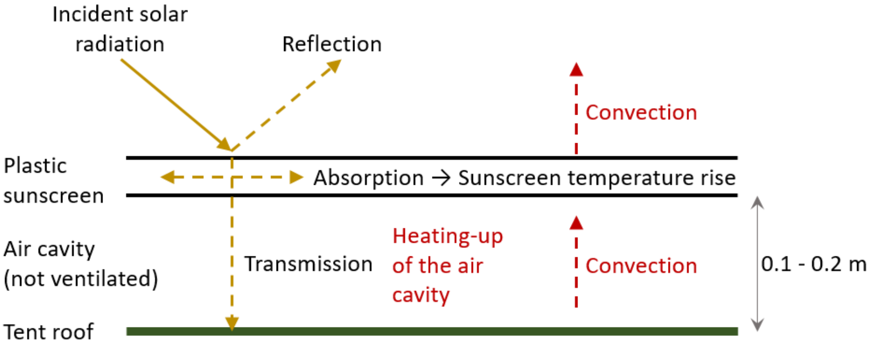


Figure 26 Reflection, absorption and transmission of solar radiation by a plastic sun-shield

SHADING NETS

The inner tent temperature can be significantly lowered by using shading nets. Examples of shading nets are shown in Figure 27. The market offers a variety of net material types differing in properties. The properties significantly affect the thermal performance of shading nets. The incident solar radiation is partly reflected by the shade net, partly absorbed and partly transmitted, as can be seen in Figure 28. The radiation that is reflected from the net to the surrounding, has no impact on the temperature of the net and the shaded tent. The absorbed radiation causes an increase in the net temperature. In order to prevent a negative impact of this temperature increase on the tent indoor temperature, the ventilation gap (air cavity) between the tent roof and the shade net must be at least 0.5 m wide (Shelter Center and Medicins Sans Frontieres, 2006). Keeping the air cavity as big as possible guarantees maximal ventilation and no negative impact of the solar radiation absorbed in the net. Therefore, the tent roof is only affected by solar transmittance. The ability of a shade net to reflect, absorb, and transmit solar radiation is described by its reflectance, absorptance, and transmittance, respectively. The sum of these three characteristics is equal to 1. The values of reflectance, absorptance, and transmittance are dependent on net features such as color, density, thickness, and glossiness. Generally, the darker color the lower reflectance, and higher absorptance. For similarly constructed nets, the higher density and thickness, the lower transmittance. According to (De Vilder, Buyle, & Virgo, 2015) black shade nets and dense aluminized nets have the best performance. The black nets are characterized by high absorptance and the aluminized ones by high reflectance, therefore their transmittance (having the biggest impact on the tent if the air cavity is well ventilated) is low. The conclusion is confirmed by (Abdel-Ghany, et al., 2019).

Figure 27 Shading nets (Military surplus army, 2020), (De Vilder, Buyle, & Virgo, 2015)

RECOMMENDATION

It is recommended to:

- Use black shade nets (high absorption) or dense aluminized ones (high reflectance) - low transmission
- Keep the distance between the roof and the shading of at least 0.5 m

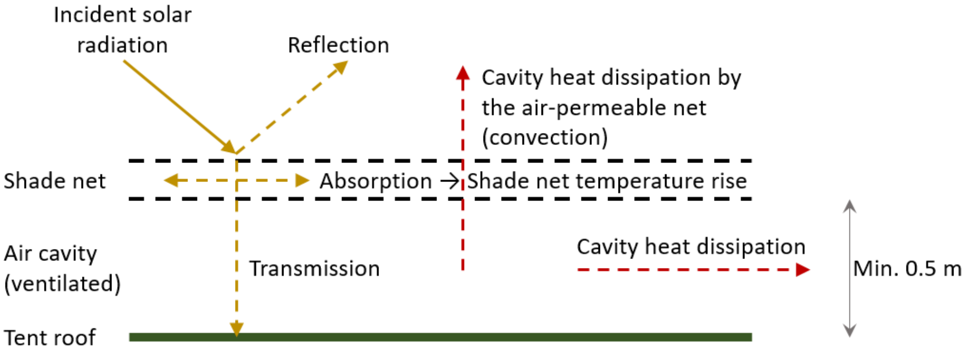


Figure 28 Reflection, absorption and transmission of solar radiation by a shade net

ANALYSIS OF SHADING MODELING APPROACHES

The principle of shading is to reduce solar radiation incident on a building. There are several ways of shading modeling in EnergyPlus which are mostly intended for buildings. To identify which approach should be used for tents' shading, three modeling methods were tested and analyzed.

The first considered method is to use the Shading:Building:Detailed object in EnergyPlus. Typically, this object is used to describe shading elements that are external to the building such as trees, fences, hills, and neighboring buildings (U.S. Department of Energy, 2018). The object allows assigning solar transmittance of the shading element. In this model, the direct radiation incident on the shading surface is transmitted as direct radiation.

The second method is to use the WindowMaterial:Shade object together with WindowProperty:ShadingControl object. In this way, perfectly diffusing shades such as drapery or translucent roller shades can be modeled. It means that all transmitted and reflected radiation is hemispherically-diffuse. The model assumes that the shading is air-permeable and that its perimeter is open.

The tent envelope is modeled as fully glazed to account for the light permeability of the fabric. The last shading modeling approach is to use an additional glass layer having properties corresponding to the shading properties. In this case, the air cavity between the tent roof and the additional layer is not ventilated.

Results for a non-shaded tent are also presented as a reference.

Figure 29 shows heating load duration curves obtained from calculations performed using the three shading modeling approaches. It can be noted that most of the time, a tent equipped with no shading (NS) has the highest heating load. This is caused by the fact the high heating loads occur at night. Shading reduces the cooling effect caused by night sky radiation. Therefore, the NS tent is not protected against the night-sky radiation and achieves the highest heating loads at night. On the other hand, during the daytime, the NS tent has lower heating demand than the shaded tent modeled using both Shading:Building:Detailed (SBD) and WindowMaterial:Shade (WMS). This is caused by the fact that shading reduces solar heat gains during the day. The heating load of the shaded tent modeled using the additional glass layer (AGL) has always lower heating loads than the reference non-shaded tent due to its higher thermal resistance. The SBD and WMS have similar heating load duration curves.

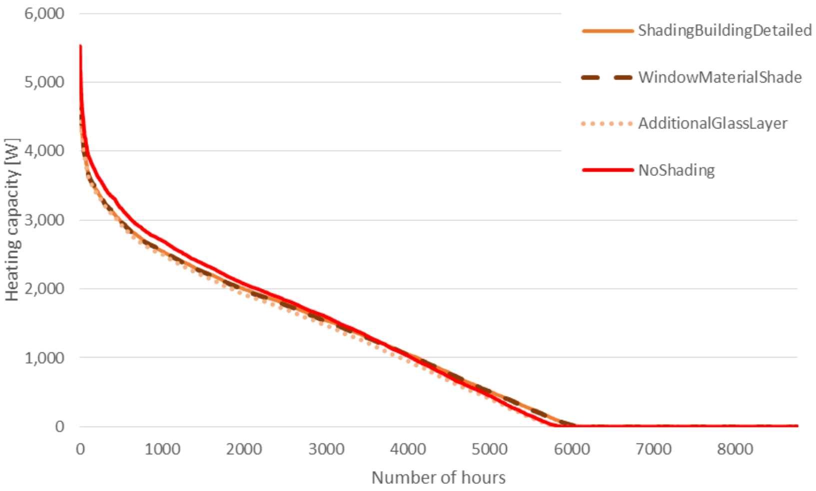


Figure 29 Heating load duration curves calculated using different shading modeling approaches

Figure 30 presents the cooling load duration curves. As expected, the tent without shading has the highest cooling loads. The AGL is in second place due to lower solar heat gains (because of lower transmittance) and higher thermal resistance. However, in the AGL model, the air cavity between the roof and the additional glass layer is not ventilated. Therefore, when solar radiation is intense the cavity temperature increases significantly. The cavity heat is conducted through the roof and the indoor air is heated-up. That is why the additional glass layer does not decrease the cooling loads significantly. The WMS shows much lower cooling loads than the reference tent without shading. The WMS reduces solar heat gains and the air cavity is ventilated through the fabric pores and the opening along the sun-shield perimeter. The SBD has slightly lower cooling loads than the WMS. In this case, the shading reduces only the solar radiation incident on the roof and the cavity between the roof and the shading is assumed to be fully ventilated.

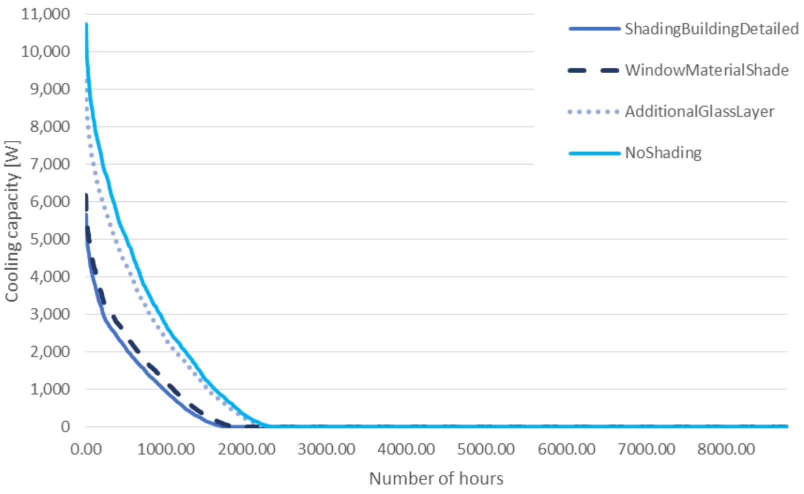


Figure 30 Cooling load duration curves calculated using different shading modeling approaches

To deeper understand the differences between heating and cooling loads obtained from calculations performed using different shading modeling approaches, roof internal surface temperatures were investigated. Figure 31 presents the inside roof temperatures calculated for a winter week. During the day, the highest roof temperature is achieved by the tent without shading due to the solar radiation incident on the roof surface. The AGL model shows a slightly lower roof temperature. The additional glass layer increases the roof thermal resistance but also decreases solar radiation reaching the inner roof layer. The WMS achieves lower roof temperatures than the AGL but much higher than the SBD model. In the WMS model, the shading device thermal model accounts for the thermal interactions between the shading and the roof, and between the shading and the outside. The thermal model also calculates the natural convection airflow between the shading and the roof. The convective airflow impacts the roof and the shading temperature. Moreover, the long-wave radiation from the sky and ground is absorbed or transmitted by the shading layer. The shading absorbs also direct and diffuse solar radiation and due to this, it increases its temperature (EnergyPlus Documentation). The SBD model shows a much lower roof temperature than the WMS. The SBD model assumes that the cavity between the roof and the shading is fully ventilated (the cavity temperature is equal to the outdoor temperature). The presence of shading does not increase roof thermal resistance. Moreover, the shading is opaque to long-wave radiation.

Figure 32 depicts the inside roof temperatures calculated for a summer week. During summer days the differences between the inner roof surface temperatures calculated using different models are much bigger than in winter due to more intensive solar radiation. Of course, the highest temperature is achieved by the tent without shading. The AGL, WMS, and SBD models are in second, third, and fourth places, respectively. The reasons are explained in the paragraph above.

During both summer and winter nights, if the sky is clear the tent without shading has the lowest roof temperature. The reason for that is the night sky radiation. The clear sky has an effective temperature of three degrees above absolute zero. The tent roof has a much higher temperature. Therefore, much more radiant heat is sent from the roof to the sky, than from the sky to the roof. As a consequence, the roof temperature is decreased. The shading screens act as a barrier to thermal radiation. Therefore, shaded tents have higher roof temperatures than the tent without shading. The highest roof temperature is achieved by the SBD model because it assumes that the shading screen is opaque to infrared radiation. The WMS and AGL show the same temperature at night because the shading material and the additional glass layer have the same infrared transmittance and infrared emissivity. If the night sky is overcast, the night sky radiation effect is much less because clouds have a much higher temperature than the universe.

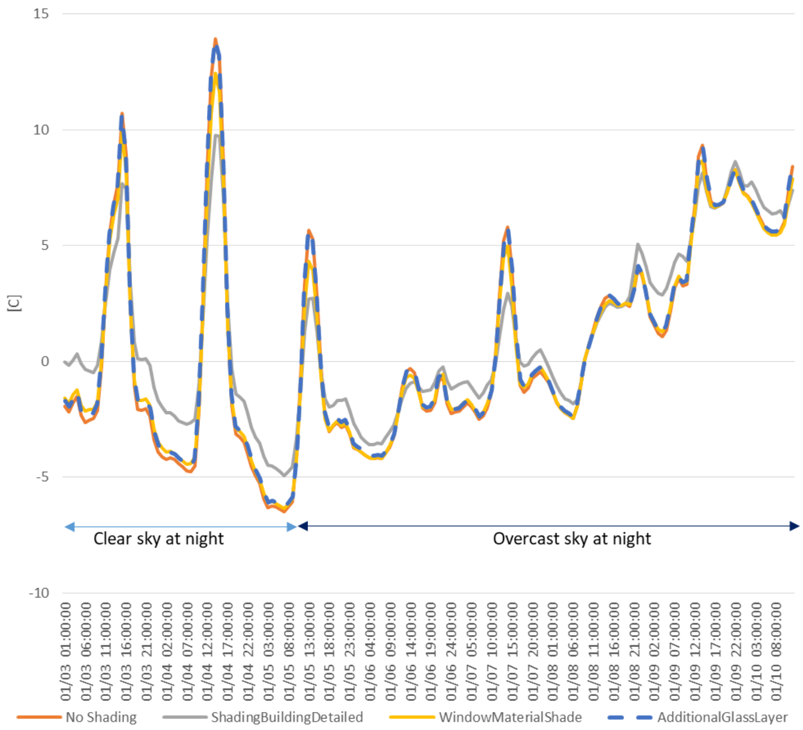


Figure 31 Inside roof temperature calculated using different shading modeling approaches – WINTER

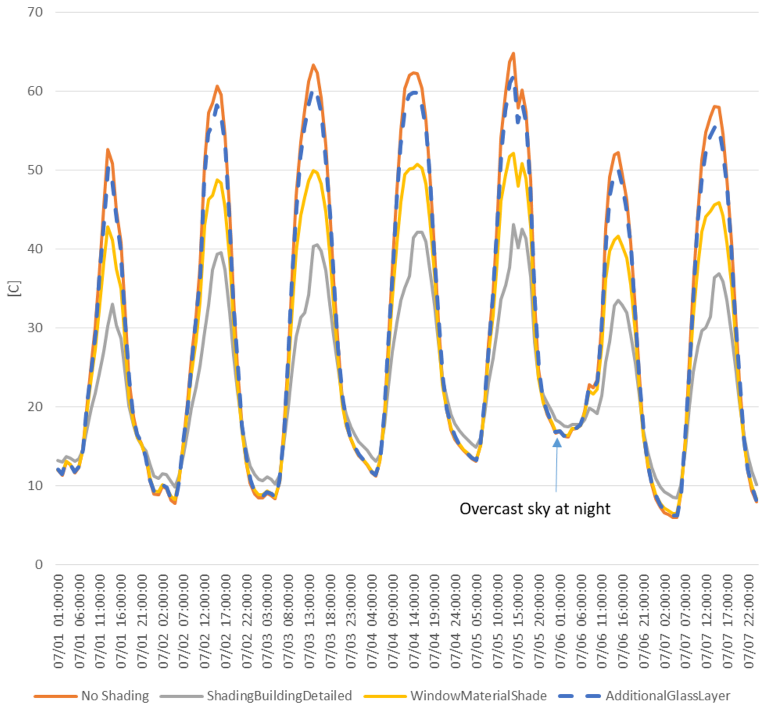


Figure 32 Inside roof temperature calculated using different shading modeling approaches – SUMMER

Figure 33 confirms the impact of the night sky radiation on the tent thermal performance. When the night sky is clear the indoor temperature of the tent without shading is lower than the outdoor temperature. This phenomenon is called thermal inversion. Due to the fact that the tent radiates heat to the sky, its indoor temperature decreases below the outdoor temperature. The presence of shading blocks the radiation and prevent thermal inversion. This positive impact of shading is also confirmed by (Montero, et al., 2013) who studied the impact of shading screens on the night-time climate of unheated greenhouses which in terms of building physics are similar to tents. When the sky is overcast, the indoor temperature is always equal to or higher than the outdoor temperature.

Also, indoor air temperatures in summer were checked. Both in summer and winter and during the day and the night, the SBD and WMS models show very similar indoor air temperatures. This explains the similarity of the heating and cooling load duration curves obtained from these two models.

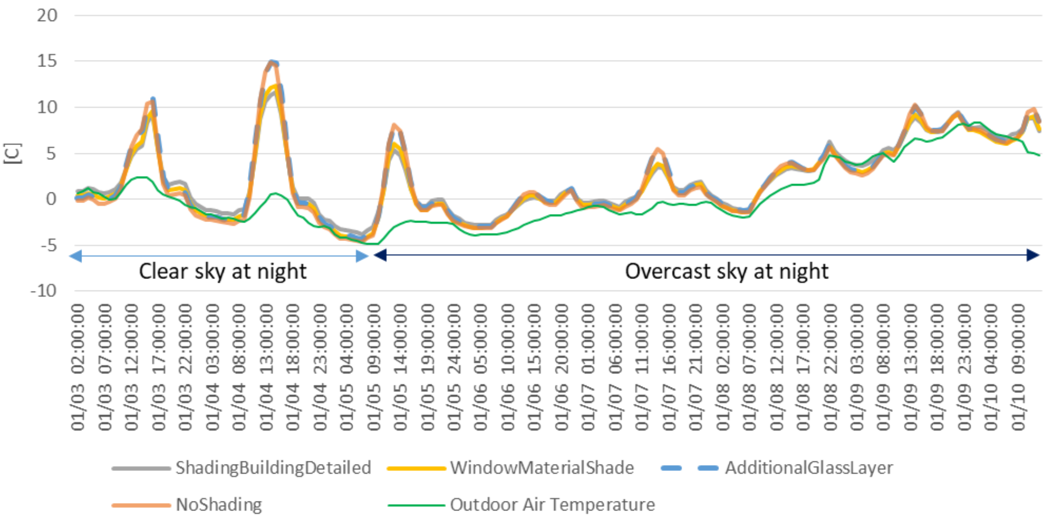


Figure 33 Indoor air temperature calculated using different shading modeling approaches vs outdoor temperature

CONCLUSION

To sum up, military tents are either shaded by a plastic sun shield or a shading net. The shading nets are air-permeable, therefore ventilation of the cavity between the roof and the shading is enhanced. The performance of the shading net is similar to the WMS and SBD models. The plastic sun-shields are made of an air-impermeable fabric and hang usually 10 – 20 cm above the tent roof. The small distance between the roof and the sun-shield, and lack of ventilation openings at the top cause that ventilation of the cavity is very poor. Therefore, the performance of plastic shading is similar to the AGL model. If the plastic sun-shield is equipped with ventilation openings, its performance is somewhere in between the AGL model and the remaining models. It is decided to use the SBD method to model shading nets. This method requires less input data (that is lacking) than the WMS method and provides similar results. The plastic sun-shields will be modeled using the most conservative approach, namely the AGL method.

The next challenge is to deal with the uncertainty of the shading material properties. The properties are not known by anybody, even not by the materials manufacturers. Reflectance, absorptance, and transmittance of the materials depend on their color, composition, glossiness, thickness, density, and weave. In the next paragraph, the impact of transmittance, absorptance, and reflectance values of shading nets and plastic sun-shields is investigated.

IMPACT OF SHADING MATERIAL PROPERTIES – SENSITIVITY ANALYSIS

Shade nets

The incident solar radiation is partly reflected by the shade net, partly absorbed and partly transmitted. The reflected radiation has no impact on the thermal performance of the net and the tent. The absorbed radiation causes an increase in the net temperature. Good ventilation ensures no effect of the solar radiation absorbed in the net on the tent. Therefore, tent thermal performance is only affected by solar transmittance. In order to investigate the impact of transmittance on heating and cooling loads, five simulations were performed assuming five transmittance values of 0.02, 0.1, 0.3, 0.5, and 0.7 (the range was set based on (De Vilder, Buyle, & Virgo, 2015)).

The impact of the shade net transmittance on the heating and cooling loads was investigated. As can be seen in Figure 34, the shade net transmittance has a negligible impact on the heating loads. However, its impact on the cooling loads is large (Figure 35). As expected, the higher the transmittance the higher the cooling loads. The differences between the cooling loads calculated assuming different transmittance values are significant, for example, the peak cooling load for the transmittance of 0.02 is 37% lower than the peak cooling load for the transmittance of 0.7. Moreover, as can be seen in Figure 36, the cooling loads increase proportionally to the transmittance value.

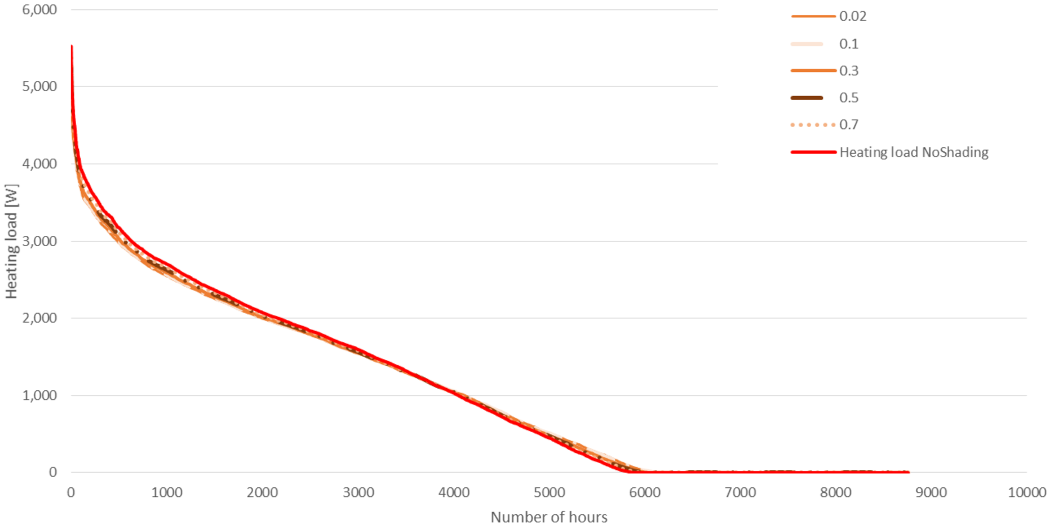


Figure 34 Heating load duration curves assuming different values of shade net transmittance

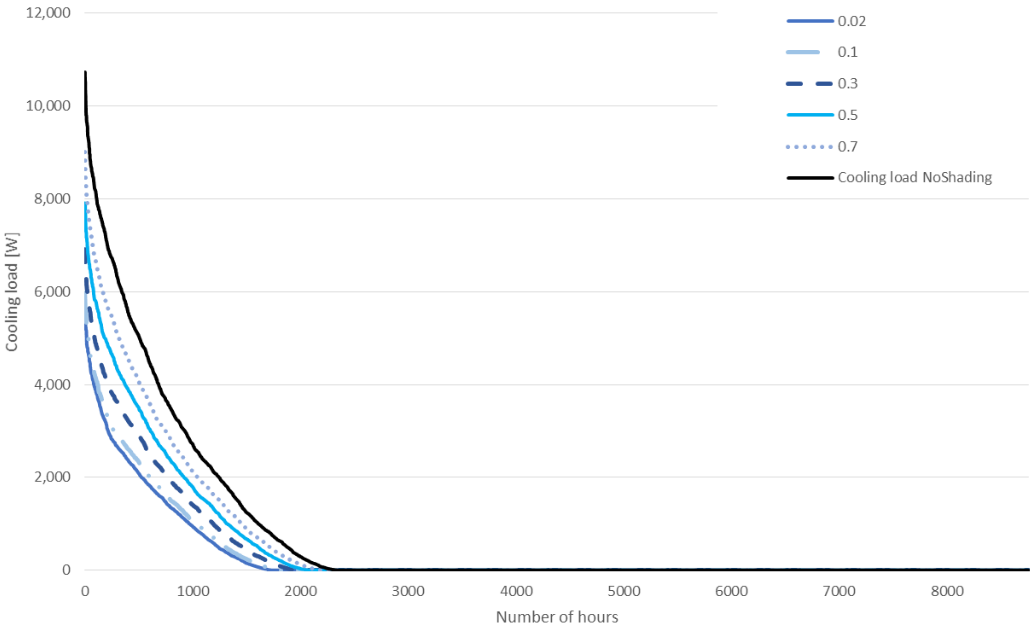


Figure 35 Cooling load duration curves assuming different values of shade net transmittance

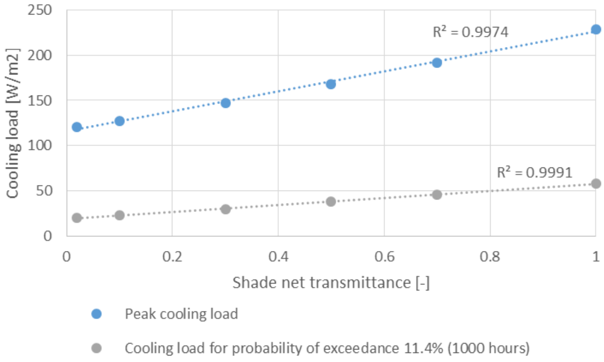


Figure 36 Cooling load vs shade net transmittance

Plastic sun-shields

In the case of the plastic sun-shields, both transmittance and absorptance influence the thermal performance of the shaded tent because of the poor ventilation of the air cavity between the roof and the sun-shield. To evaluate the impact of these parameters on the cooling loads, one hundred simulations were performed, assuming different values of transmittance (T), absorptance (A), and reflectance (R). The transmittance range was 0 – 0.2 (based on (Mehgies Mehler Texnologies, 2017)). The reflectance and absorptance were calculated using the formulas below.

$$R + A = 1 - T$$

$$R = r \cdot (R + A)$$

$$A = (R + A) - R$$

Where r is a random number from the range from 0 to 1. The set of random numbers r was created using the Latin Hypercube Sampling method. The method allows for obtaining a uniformly distributed sample.

Figure 37 shows a graph presenting the values of transmittance, absorptance, and reflectance together with the peak heating and cooling loads. As can be seen, the parameters do not affect the peak heating load. However, of course, they affect the peak cooling loads. Figure 38 shows one hundred cooling load duration curves obtained from the simulations assuming different values of transmittance, absorptance, and reflectance. The peak cooling loads range from 5.6 kW to 11.3 kW. To get a better understanding of the impact of the shading properties on the cooling load, a 3D scatter plot showing the dependency between transmittance, absorptance, and reflectance, and peak cooling loads is shown in Figure 39. It can be noted that the peak cooling loads increase together with increasing absorptance and transmittance, as expected. Absorptance has the largest impact due to its wide range (0 – 1) and therefore also large variability in comparison to the transmittance (0 – 0.2). Absorptance is important because it is responsible for the temperature increase in the cavity between the roof and the shading. If the transmittance is high, the absorptance is very high and the reflectance is very low, the peak cooling load is even slightly higher than for the reference tent without shading. It means that the high air cavity temperature overweighs the reduction of transmitted solar radiation and the increase of thermal resistance.

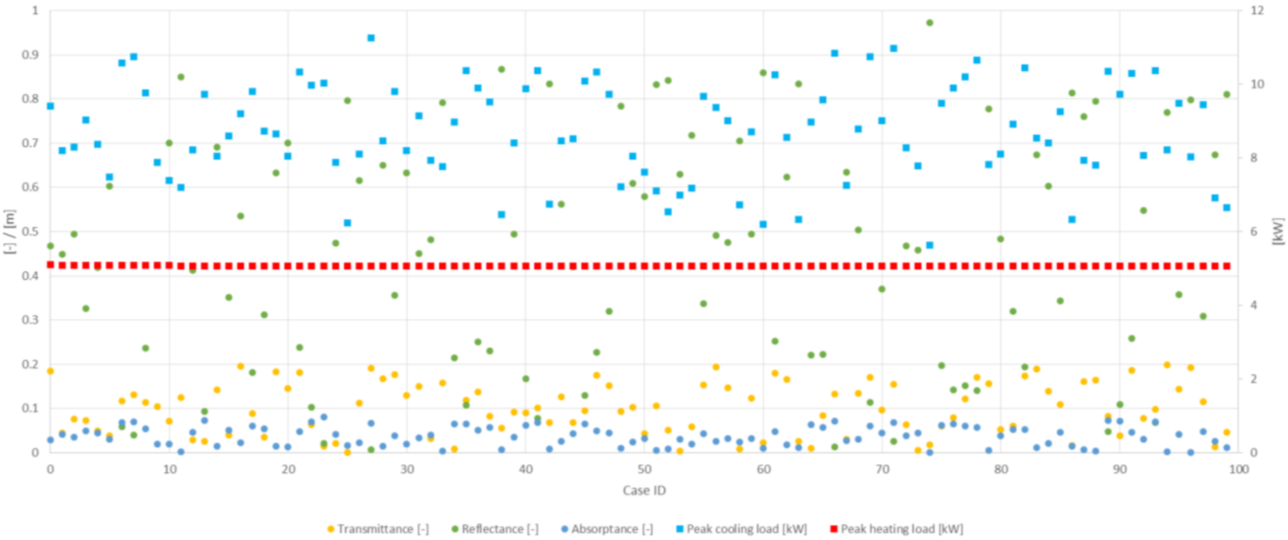


Figure 37 Peak heating and cooling loads vs air cavity thickness, transmittance, reflectance, and absorptance of a plastic sun-shield

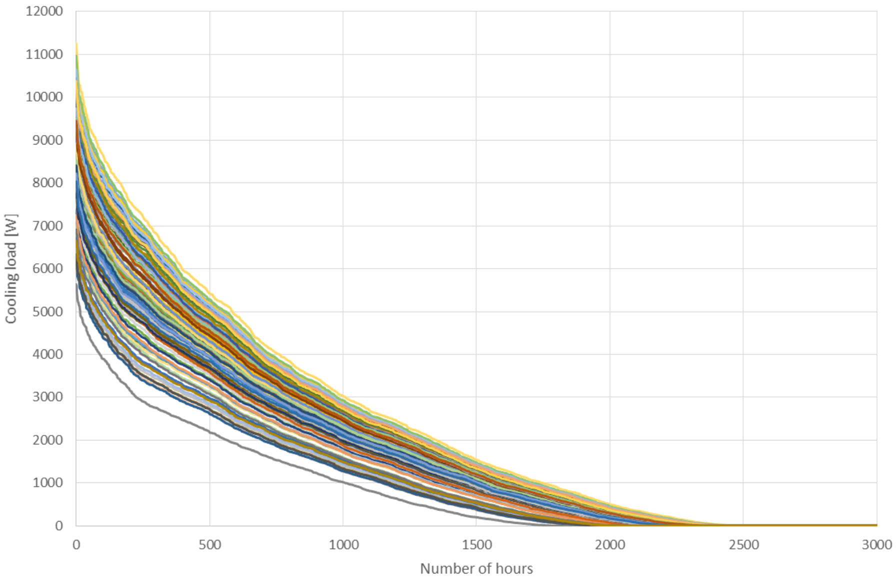


Figure 38 Cooling load duration curves assuming different values of plastic sun-shield transmittance, absorptance, and reflectance

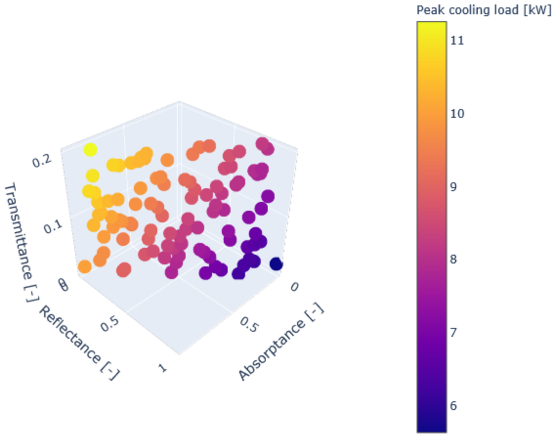


Figure 39 Peak cooling load vs transmittance, reflectance, and absorptance of a plastic sun-shield

CONCLUSION

To conclude, military tents can be shaded either by a plastic sun-shield or a shading net. The shading nets are air-permeable and the cavity between the tent roof and the shading is ventilated. The SBD method will be used to model shading nets. The plastic sun-shields are made of an air-impermeable material and hang a small distance above the tent roof. Therefore, the cavity ventilation is very poor. The plastic shading will be modeled using the AGL model.

Properties of shading materials depend on their color, composition, glossiness, thickness, density, and weave. Usually, the properties are known neither to the DST developers and users nor to the tents and shading manufacturers. The analysis showed that the properties of shading materials have a big impact on the cooling and heating loads of a shaded tent. Therefore, without knowledge about the properties, it is not possible to give unambiguous results. There are two possible solutions. The first solution is to allow the DST user to fill in the properties (if they are known to the user) via the DST interface. Then, the DST can provide unambiguous results. The second solution is to allow the user to fill in less detailed information, for example, the color of the shading. As it is known, colors have different shades, or fabrics have different glossiness. Due to this, fabrics of the same color may have different properties. However, these properties can be captured in a certain range for which the calculations can be performed. In this case, results would be presented as a range instead of a single number.

5.2.6 UNCERTAINTY ANALYSIS

Uncertainties pose a large challenge for building performance simulation tools. The source of uncertainties can be limited or inaccurate information about the physical properties of the simulated building (for example material properties or building airtightness), about the building occupancy, and climate change.

Thermal modeling of military tents involves much more uncertainties than the modeling of conventional buildings. Detailed information about materials' thermal properties is often unknown because the manufacturers are not obligated to measure these properties. The assessment of tent air-tightness is very difficult since it is not only dependent on the tent construction, presence of ventilation openings, the openness of windows and door, and envelope material properties, but also on the quality of the tent assembly. Also, knowledge about the operation of the military tents is often very uncertain because the tents can have different functions which are sometimes not known in advance.

The goal of this study was to get a better understanding of the impact of input uncertainties on the simulation outputs and to find a solution to keep the output uncertainty in a sensible range maintaining integrity. By sensible range is meant that the uncertainty cannot impair the usefulness of the DST.

In this study, the information about the tent geometry, operation, and weather conditions is considered as known to keep the output uncertainty in sensible ranges allowing the DST to remain meaningful and useful. The uncertainties related to material properties and infiltration were taken into account.

The uncertainty analysis was performed to estimate the range of simulation outputs considering the uncertainty of input parameters related to the physical properties of tents. The following uncertain parameters were taken into account:

- Transmittance, absorptance, and reflectance of the tent fabric
- Infiltration rate
- Fabric thermal resistance
- Shading properties (in case the tent is shaded)
  - Shading net transmittance
  - Plastic fabric sun shield transmittance, absorptance, and reflectance

The maximum and minimum values of transmittance, absorptance, and reflectance of the fabrics are presented in Table 14. The values were taken from the materials’ technical specification (Mehgies Mehler Texnologies, 2017), (Mehgies - Textiles to Transform, 2017). It must be noted that it is assumed that the values are constant for the whole solar spectrum. This simplification was made because more detailed information is not available. The maximum and minimum values of the infiltration rate are presented in Table 15 and were established based on the literature review discussed in subsection 5.2.2. The maximum and minimum values of the fabric thermal resistance are shown in Table 16. The values were provided by the manufacturer of tents Schall that often supplies the Dutch army. The maximum and minimum values of shading nets' transmittance are listed in Table 17 and were established based on the experiments performed by (Abdel-Ghany, et al., 2019). The values of transmittance, reflectance, and absorptance of the plastic fabric sun shield are the same as for the tent fabric and are listed in Table 14. Figure 40 visualizes the considered configurations. For each configuration, calculations were performed twice – with the most optimistic and the most pessimistic settings.

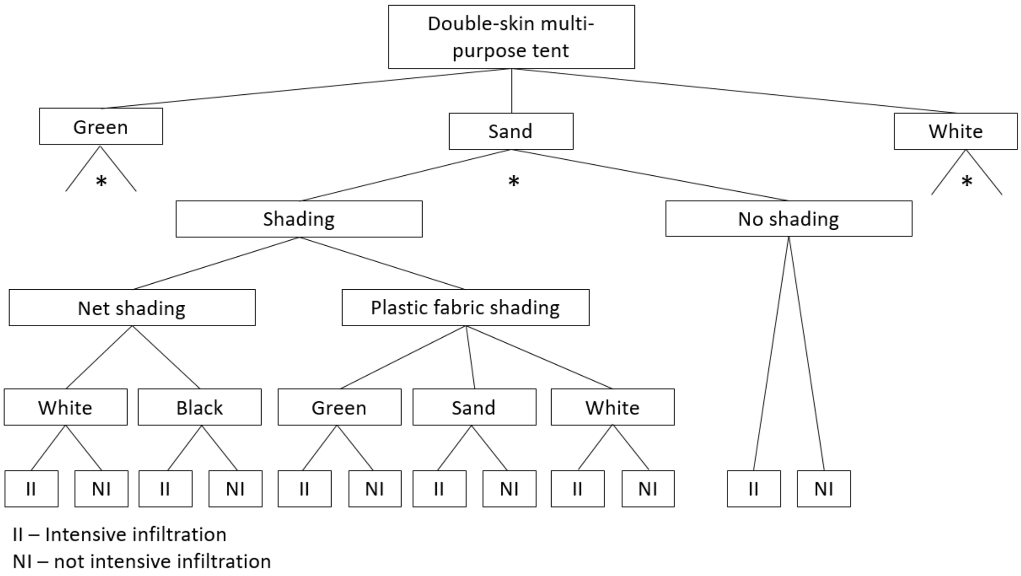


Figure 40 Considered scenarios (36 in total), each was calculated twice – with the most optimistic and the most pessimistic settings

Table 14 Absorptance, reflectance, and transmittance of green, white and sand PVC coated PE fabrics based on (Mehgies Mehler Texnologies, 2017), (Mehgies - Textiles to Transform, 2017), and (Knippers, Cremers, Gabler, & Lienhard, 2011)

		Green	White	Sand
Absorptance	max	0.9	0.15	0.35
	min	0.8	0.04	0.15
Reflectance	min	0.07	0.75	0.5
	max	0.2	0.96	0.85
Transmittance	max	0.03	0.1	0.15
	min	0	0	0

Table 15 Assumed infiltration rates

Infiltration rate [ACH]			
Not intensive		Intensive	
min	max	min	max
1	2	2	4

Table 16 Assumed fabric thermal resistances

Fabric thermal resistance [m2K/W]	
min	max
0.15	0.20

Table 17 Assumed shading nets' transmittances, based on (Abdel-Ghany, et al., 2019)

Shading net transmittance [-]			
Black		White	
min	max	min	max
0.3	0.5	0.4	0.65

Figure 41 shows the differences in peak heating and cooling loads between the optimistic and the pessimistic cases. For heating, the differences are about 20-30%. For cooling, they are much larger – up to almost 80% for sand and white tents. The reason for that is the impact of solar radiation and the uncertainty of the transmittance, absorptance, and reflectance values.

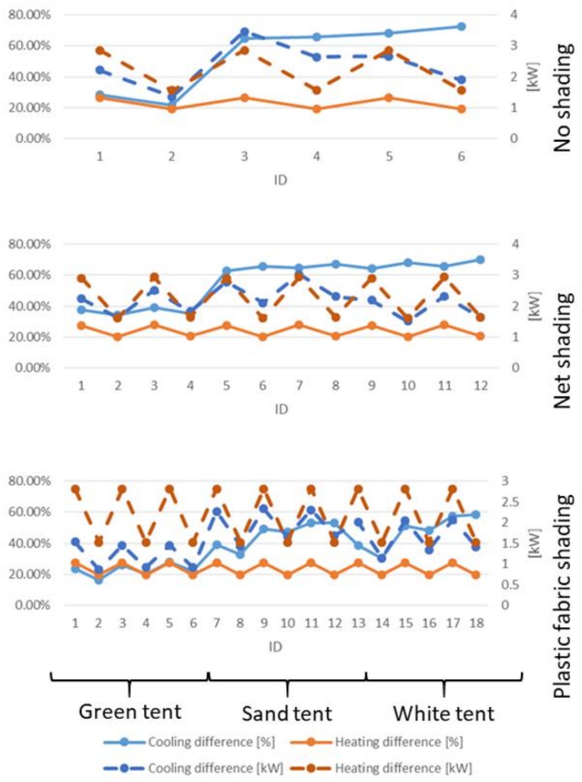


Figure 41 Peak heating and cooling loads – the difference between "optimistic and pessimistic cases"

Such large output uncertainty ranges are not acceptable because they make the tool not meaningful and useless. Preferably, the uncertainty should be decreased by getting more accurate knowledge about the uncertain parameters. However, in this case, it is not possible because (1) more detailed information is not available both for the DST developer and user, (2) tents can be made of different materials having different properties. Therefore, the only way to decrease the uncertainty is to ask the DST user for more information to narrow down the input parameters uncertainty range.

From the wavy shape of the lines in Figure 41 representing the differences in heating and cooling loads in kW, it may be concluded that the infiltration affects the heating and cooling load significantly (uneven IDs represent intensive infiltration and even IDs represent not intensive infiltration). Therefore, the uncertainty of the infiltration rate has a large impact on the overall uncertainty of the results. In order to reduce the uncertainty caused by the infiltration, the infiltration rate uncertainty range needs to be reduced. However, to ensure that the infiltration rate is not underestimated the values should remain on the conservative side.

To test this approach and to investigate the impact of the infiltration rate uncertainty, in the next step the calculations were done assuming a constant infiltration rate. For the sake of simplicity, the next graphs concern unshaded tents. However, similar conclusions were drawn for the tents shaded with the net and the plastic fabric. The infiltration rate was assumed to be constant and equal to 2 ACH. Figure 42 shows the differences between the optimistic and the pessimistic scenario under the constant infiltration rate assumption. For heating, the difference is close to 0. For cooling, it decreased significantly in comparison to the first graph in Figure 41. The uncertainty of the infiltration rate affects to a large extent the uncertainty of the heating and cooling loads. Therefore, as expected, the uncertainty range of the infiltration rate must be relatively small because large ranges make the DST output confusing and useless.

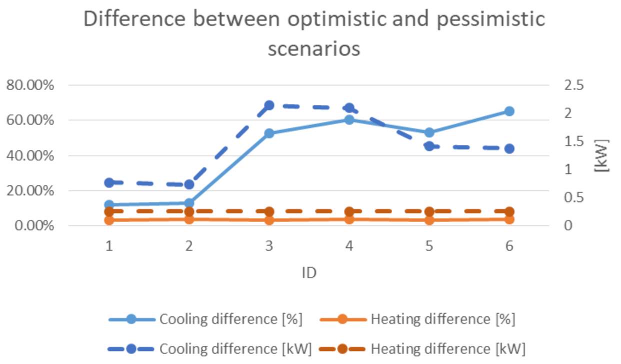


Figure 42 Peak heating and cooling loads – the difference between "optimistic and pessimistic scenarios" – Constant infiltration rate of 2 ACH

The second solution for reducing the output uncertainty is to get from the user more information about the fabric the tent or shading is made of. Of course, the user cannot be asked to provide quantitative data about the properties of the materials because usually, he does not have this information. Therefore, the idea is to ask the user if the material permits light or not. This feature of the material can easily be visually assessed by the user and allows decreasing the uncertainty of inputs related to the materials' transmittance, absorptance, and reflectance. Figure 43 shows again the differences between the optimistic and the pessimistic scenarios. In this case, the infiltration rate is fixed, and two types of tent fabric are distinguished – opaque and light-permeable. Comparing with the numbers shown in Figure 41 and Figure 42, the uncertainties of heating and cooling loads are significantly lower.

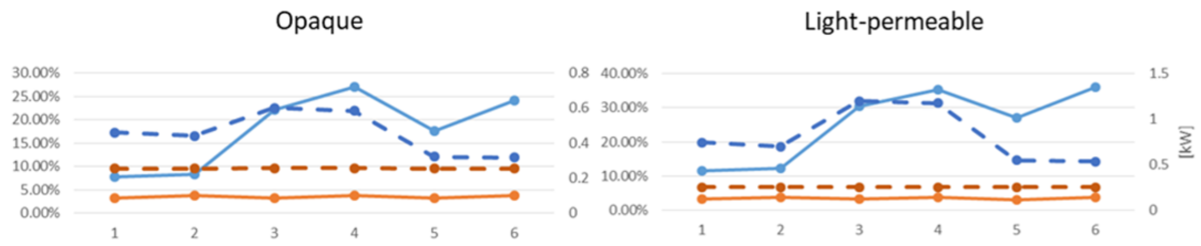


Figure 43 Peak heating and cooling loads – the difference between "optimistic and pessimistic scenarios" – Constant infiltration rate of 2 ACH and colors split into opaque and light-permeable

CONCLUSION

The uncertainties in the simulation inputs cause significant uncertainties in the simulation output. The best way to reduce the output uncertainties is to gain more information and to reduce the input uncertainty. However, in this case, it is not possible because more detailed information about tents' physical properties is not available for both the DST developer and user. Moreover, tents can be made of a variety of materials and the DST must consider it. The only way to reduce the uncertainty is to get more information from the DST user. This information cannot be quantitative because the user does not have such knowledge. Therefore, the only solution is to ask the user for more qualitative information.

The user should specify if he expects intensive or not intensive infiltration in the tent. This is a subjective question that should be answered based on the knowledge about the intended function of the tent, the military camp site and layout, and if the tent fabric is perceived as "breathing". The input uncertainty range of the infiltration rate should not be very wide because it would result in a wide output uncertainty range making the DST confusing and not useful. Therefore, it is better to assume a narrower input uncertainty range but more conservative infiltration rate values.

The second measure to decrease the output uncertainty is to ask the user if the tent fabric is fully opaque or light-permeable. This feature can be easily assessed by the user by visual examination. This information allows the reduction of the uncertainty ranges of the fabric transmittance, reflectance, and absorptance.

5.3 CONSIDERATIONS ON THERMAL COMFORT MODELS

One of the main goals of HVAC systems is to maintain thermal comfort (Cheng, Niu, & Gao, 2012). According to the ASHRAE standard "Thermal Environmental Conditions for Human Occupancy" (ASHRAE 55, 2010), thermal comfort is defined as "condition of mind that expresses satisfaction with the thermal environment". According to the standard, there are six factors for defining conditions for thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, airspeed, and humidity. The metabolic rate is associated with occupant activities and related body heat release. Another personal factor influencing thermal comfort sensation is the clothing insulation level. Air temperature is the most recognizable parameter impacting thermal comfort which is regulated by commonly used thermostats. Air temperature determines convective heat dissipation. Radiant temperature is associated with surfaces' temperature and thermal radiation effects. Air humidity affects the evaporative heat transfer process from the human body. Airspeed impacts the rate of convective cooling of the body and evaporative heat transfer rate (ANSI/ASHRAE, 2016). Airspeed, air temperature, and mean radiant temperature affect the operative temperature. The operative temperature is defined as “the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment” (de Dear J. , 1998). Therefore, the operative temperature is the one directly influencing thermal sensation. The operative temperature is calculated as (Enescu, 2017):

$$T_{op} = \frac{(T_{MR} \cdot h_r + T_{db} \cdot h_c)}{(h_r + h_c)}$$

Where T_{db} is the air dry-bulb temperature, T_{MR} is the mean radiant temperature, h_r is the radiative heat transfer coefficient, and h_c is the convective heat transfer coefficient. If T_{MR}-T_{db} < 4K (Enescu, 2017):

$$T_{op} = \frac{(T_{MR} + T_{db})}{2}$$

Tents are characterized by a low thermal resistance of the envelope. Therefore, the outdoor temperature and solar radiation significantly affect the envelope's internal surface temperature. For example, (Fosas, Albadra, Natarajan, & Coley, 2018) reports that the internal surface of the envelope of refugee shelters in Jordan is often too hot to touch. The internal surface temperature is directly related to the radiant temperature which is one of the factors affecting thermal comfort. On one hand, in the heating season, the indoor air temperature is much higher than the surface temperature. On the other hand, in the cooling season, the indoor temperature is much lower than the surface temperature. Thus, sometimes even if the setpoint air temperature is maintained, the thermal comfort is disturbed because of the radiant temperature.

The DST is required to demonstrate the impact of climate on the tent occupants’ thermal comfort. To meet this requirement, a way to measure thermal comfort must be defined. Usually, thermal comfort is measured with the use of thermal comfort models. The models are developed by researchers, professional associations, or standardization organizations. The models are valid for the conditions assumed by their developers. Currently, there exists no thermal comfort model developed for tents. That is why this review of existing thermal comfort models was performed. The aim was to find a model that is the most suitable for this purpose.

I must be noted that besides the six thermal comfort parameters that were mentioned at the beginning of this subsection (metabolic rate, clothing insulation, air temperature, radiant temperature, airspeed, and humidity), there are other factors influencing thermal comfort and body heat balance, for example, food and drink, acclimatization, body shape, subcutaneous fat, age, gender and state of health (Auliciems & Szokolay, 2007). However, these factors are difficult to quantify and usually they are not taken into account in thermal comfort analysis. Because people are different from nature, both psychologically and physically, it is difficult to satisfy everybody in a room (ASHRAE 55, 2010). Thermal comfort can be also disturbed by draught, radiant temperature asymmetry, vertical air temperature differences, and floor temperature (EN 15251, 2007). However, these factors are also not included in widely accepted thermal comfort models. Air humidity is considered in the models in terms of its impact on human body heat balance. Long-term high indoor air humidity results in microbial growth and long-lasting low humidity causes dryness and irritation of eyes and airways (EN 15251, 2007), and these effects are also not taken into account by the models.

ASHRAE-55 THERMAL COMFORT MODELS

An internationally accepted model for thermal comfort prediction is the Fanger's PMV-PPD model (Predicted Mean Vote - Predicted Percentage of Dissatisfied). Based on Fanger's model, ASHRAE developed its graphic comfort zone method for typical indoor environments. The comfort zone is defined by combinations of the six key factors for thermal comfort for which the PMV is within the range -0.5 and 0.5, and the PPD is less than 10%. Figure 44 shows an example of the graphical comfort zone method. ASHRAE provides also an analytical method that requires calculations using the ASHRAE Thermal Comfort Tool (http://comfort.cbe.berkeley.edu/). The graphical and analytical methods can be modified to consider higher airspeeds using the Elevated Airspeed Method. An alternative approach proposed by ASHRAE is Adaptive Method which can be used to determine acceptable thermal conditions, especially in occupant-controlled naturally conditioned spaces. Occupant-controlled naturally conditioned spaces are defined as those spaces where the thermal conditions are regulated primarily by the occupants through the opening and closing of windows. The alternative model, called the adaptive model, is valid for spaces where the occupants are in near-sedentary physical activity and are free to adapt their clothing. For such spaces, the standard proposes to determine acceptable indoor operative temperatures from the graph shown in Figure 45. The adaptive model is based on the hypothesis that contextual factors and thermal history change the occupant's thermal expectations and preferences. It means that during long-lasting warm periods or in warm climates, people generally prefer higher indoor temperatures than during long-lasting cold periods. Thermal adaptation can be behavioral, physiological, and psychological (de Dear, Brager, & Cooper, 1997).

Limitations of the four methods (graphical, analytical, elevated airspeed, and adaptive) are listed in Table 18.

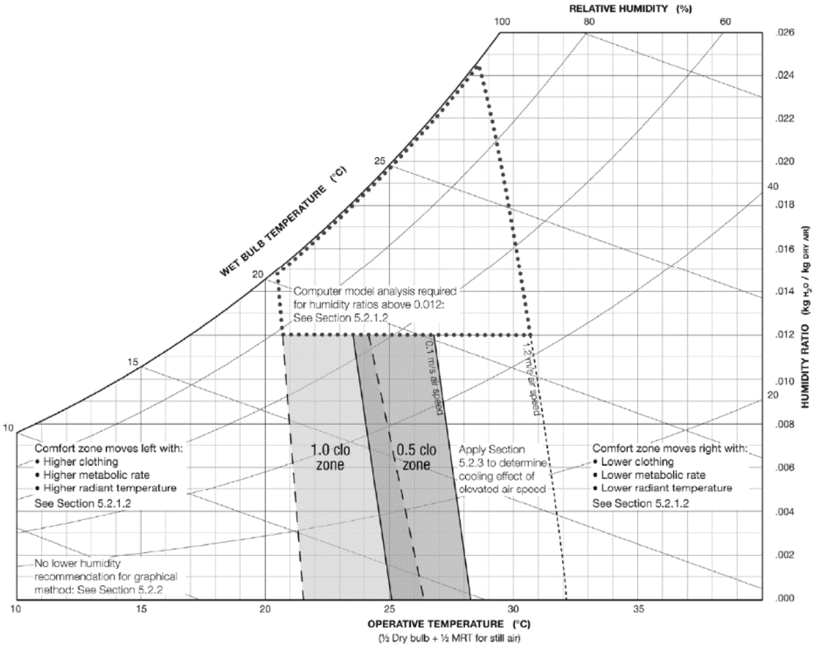


Figure 44 Graphical Comfort Zone Method based on Fanger's thermal comfort model: Acceptable range of operative temperature and humidity (ASHRAE 55, 2010)

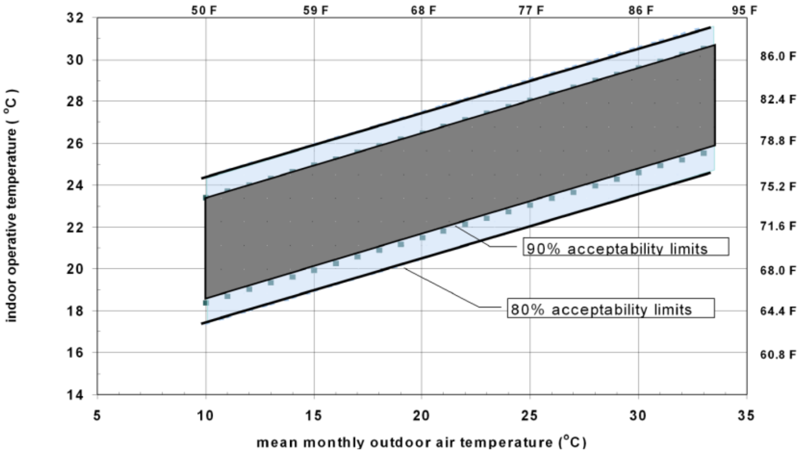


Figure 45 Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE 55, 2010)

Table 18 Factors limiting the applicability of ASHRAE thermal comfort methods, adopted from (ANSI/ASHRAE, 2016)

Comfort Zone Method	Airspeed	Humidity ratio	Metabolic rate	Clothing insulation	Comment
Graphical method	<0.2 m/s	<0.012 kg H2O/ kg dry air	1.0 – 1.3 met	0.5 – 1.0 clo	Simple but limited in usability
Analytical method	<0.2 m/s	-	1.0 – 2.0 met	0 – 1.5 clo	Requires calculations using ASHRAE Thermal Comfort Tool
Elevated air speed method	>0.2 m/s	-	1.0 – 2.0 met	0 – 1.5 clo	Modifies graphical or analytical method to account for increased air speed
Adaptive method	-	-	1.0 – 1.3 met	Free to adjust within a range at least as wide as 0.5 to 1.0 clo	Applies only to naturally air-conditioned spaces; Air dry-bulb temperature close to mean radiant temperature; No cooling installed; Heating not operating; Occupants control openings; Prevailing mean outdoor air temperature 10°C - 33.5°C

In terms of the usability of the methods for the DST output, all of them are not completely appropriate. The adaptive method applies to non-conditioned spaces only. Due to this, the outdoor temperature range is between 10 and 33.5°C. This temperature range does not cover the annual outdoor temperatures range. Another limitation of the Adaptive Method is the assumption that the mean radiant temperature is close to the indoor air temperature. Because of the low thermal resistance of the tent's envelope, the inside surface temperatures are very high in summer and very low in winter. Therefore, the difference between the mean radiant temperature and the indoor air temperature is large. The next limitation is the upper limit of clothing insulation of 1.0 clo which corresponds to typical winter indoor office clothing. Winter military clothing is characterized by much better insulation properties than winter office clothing.

The mean problem of the PMV-PPD methods (graphical, analytical, and elevated airspeed) is the use of air humidity for representing thermal comfort. Since there is no humidity control in the tents, usage of the air humidity as a thermal comfort indicator can be misleading for the DST users.

THERMAL COMFORT ACCORDING TO STANDARD EN 15251

For heating and cooling load calculations of mechanically heated and cooled buildings, European standard (EN 15251, 2007) recommends using the Fanger's PMV-PPD method with assumed levels of activity and clothing insulation. For a building with no mechanical cooling, the recommended values of indoor temperature should be taken from the adaptive thermal comfort graph provided by the standard and shown in Figure 46. The comfortable range of operative temperature is presented as a function of the running mean outside temperature. The running mean outside temperature is defined as the exponentially weighted running mean of the daily mean external air temperature and can be calculated using the equation below:

$$T_{rm} = (1 - \alpha) \cdot \{T_{ed-1} + \alpha \cdot T_{ed-2} + \alpha^2 \cdot T_{ed-3} + \cdots\}$$

Where:

T_{rm} – running mean temperature for today

T_{ed-1} – daily mean external temperature for the previous day

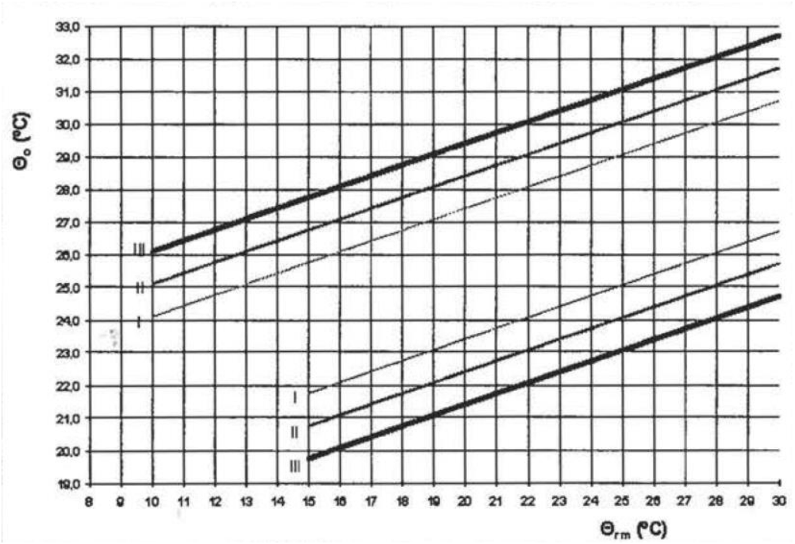
T_{ed-2} – daily mean external temperature for the day before and so on

α– constant between 0 and 1, recommended 0.8.

The operative temperature ranges depicted in Figure 46 correspond to three categories of indoor spaces. The description of these categories can be found in Table 19. The operative temperature limits are valid only if the conditions stated by the standard (EN 15251, 2007) and listed below are met:

1. Thermal conditions in the space are regulated mainly by the occupants through the opening and closing of windows.
2. The space should be equipped with openable windows that are reachable by occupants.
3. There is no mechanical cooling in operation.
4. Mechanical ventilation can be used.
5. Low energy cooling methods such as fans, shutters, night ventilation can be used.
6. The space can be equipped with a heating system, however, the ranges are valid only for seasons when the heating system is off.
7. Occupants are in near sedentary activity with the metabolic rate between 1 and 1.3 met.
8. There are no strict clothing policies and occupants can freely adapt their clothing insulation.
9. The stated operative temperature limits apply when the running mean outdoor temperature is between 10°C and 30°C.

According to the standard, in the heating season, if the outdoor temperature is below 10°C, the upper limit of comfortable temperature as for mechanically air-conditioned buildings should be used and if the outdoor temperature is below 15°C, the lower temperature limits as for the mechanically air-conditioned building should be applied.



Θ_{rm} = Outdoor Running mean temperature °C.

Θ_0 = Operative temperature °C.

Figure 46 Acceptable indoor air temperatures for buildings with no mechanical cooling according to (EN 15251, 2007)

Table 19 Indoor spaces categories, adapted from (EN 15251, 2007)

Category	Description	PPD [%]	PMV	Limit for non-mechanically cooled buildings
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	< 6	-0.2 < PMV < +0.2	± 2 K
II	Normal level of expectation and should be used for new buildings and renovations	< 10	-0.5 < PMV < +0.5	± 3 K
III	An acceptable, moderate level of expectation and may be used for existing buildings	< 15	-0.7 < PMV < +0.7	± 4 K

THERMAL COMFORT ACCORDING TO GUIDELINE ISSO 74

The Dutch guideline (ISSO-publicatie 74, 2014) provides a hybrid method of thermal comfort evaluation that combines elements of non-adaptive comfort standards with elements of adaptive standards. The method distinguishes two types of spaces. Spaces having at least one operable window per façade length of 3.6 m and no active cooling systems are categorized as type α. Spaces having no operable windows or having operable windows but being equipped with an active cooling system are categorized as type β. Furthermore, the user of the method must determine the space's performance class. Four performance classes are available. Classes A, B, and C correspond to classes I, II, III defined in the standard (EN 15251, 2007). Class D corresponds to limited expectations and should be used only for temporarily used buildings. The required indoor temperature ranges as a function of running mean outdoor temperature are presented in Figure 47. The running mean outdoor temperature is defined the same way as in the standard (EN 15251, 2007). The (ISSO-publicatie 74, 2014) is applicable for the running mean outdoor temperatures range between -5°C and 22°C. Requirements regarding indoor temperature level of class A spaces are the same as for class B. The graph shown in Figure 47 can be used if the activity level is at most 1.4 met and occupants can adjust their clothing levels between 0.5 and 1.0 clo. However, for higher activity levels and higher clothing insulation levels, the guideline suggests using the type β upper limits together with a correction. (Boerstra, van Hoof, & van Weele, 2015)

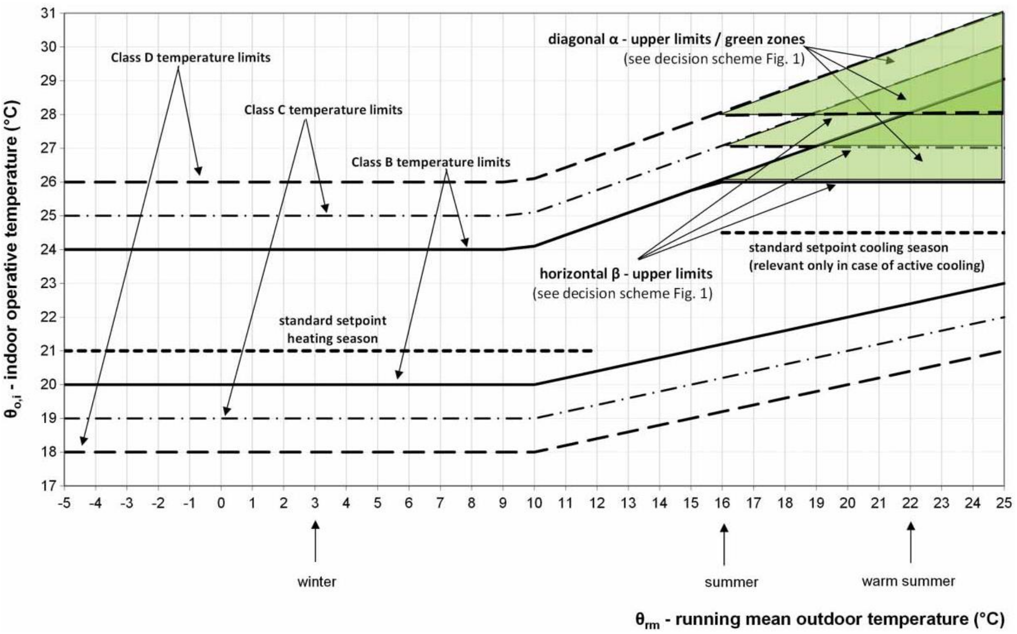


Figure 47 Requirements for the indoor operative temperature according to standard (ISSO-publicatie 74, 2014)

DEPENDENCY BETWEEN THERMAL COMFORT REQUIREMENTS AND THE LOCAL CLIMATE

It is argued that the traditional PMV-PPD thermal comfort model ignores climatic, cultural, societal, and contextual aspects of thermal comfort. On the other hand, the adaptive model takes into consideration the climatic context, occupants' past thermal experiences, and adaptation possibilities (Singh, Mahapatra, & Atreya, 2011). However, studies have shown that thermal requirements of occupants and their level of adaptation are different in different climatic zones and therefore there is no universal adaptive comfort model that can be used for every case.

(Singh, Mahapatra, & Atreya, 2011) performed a thermal comfort survey within three climatic zones of India – warm and humid, cool and humid, and cold and cloudy, in four different seasons. Based on the results, the authors developed theoretical comfort models using adaptive coefficients for the three climatic zones and the four seasons. Different values of the adaptive coefficients show that occupants adapt differently in different climatic zones and seasons. The authors claim that it is necessary to perform extensive experiments in different climatic zones and calculate more accurate values of the adaptive coefficients.

(Yamtraipat, Khedari, & Hirunlabh, 2005) surveyed 1520 participants in air-conditioned buildings in different climatic regions of Thailand. The authors studied the impact of education level and acclimatization on the thermal comfort perception. The authors concluded that comfortable thermal conditions for Thais are different from those widely used. The temperature of 26°C and 50-60% relative humidity is a comfortable condition for the whole country. Moreover, it was pointed out that people who use home air-conditioning and highly educated people prefer lower air temperature.

(Thapa, 2019) conducted survey-based research on thermal comfort in residential houses in a high altitude, cold region in India. The author points out that the obtained comfort temperature ranges do not comply with the ASHRAE standard 55 graphical method and that the comfort zone for cold climatic regions should be extended to the left of the psychrometric chart. The proposed lower and upper temperature limits are 13.8°C and 20.6°C respectively. The proposed boundaries of relative humidity are 20% and 90%.

(Han, et al., 2007) performed a thermal comfort survey with 110 respondents in three cities in the hot and humid climate of central-southern China. The authors concluded that the neutral operative temperatures obtained from the survey data are higher than the neutral operative temperatures calculated from the PMV Fanger's model. This confirms that climatic differences impact comfort perception because of different adaptation of humans.

(Manu, Shukla, Rawal, Thomas, & de Dear, 2016) proposed an India Model for Adaptive Comfort based on surveys performed in three seasons in five climate zones. The authors observed that occupants in naturally ventilated Indian offices are more adaptive that it is predicted by ASHRAE or European standards. The authors claim that the adaptive model is valid and robust for both naturally ventilated and air-conditioned modes of operation in mixed-mode buildings.

To sum up, the thermal requirements of occupants and their level of adaptation are different in different climatic zones and therefore there is no universal adaptive comfort model that can be used for every case.

POSSIBLE SOLUTIONS FOR THERMAL COMFORT REPRESENTATION IN THE DST

The literature review on the thermal comfort models showed that any of the widely accepted models is not completely suitable for the evaluation of thermal comfort in military tents. There are several solutions, however, each of them has its own pros and cons. The proposed solutions together with their advantages and disadvantages are listed in Table 20.

The advantages and disadvantages of the solutions were analyzed and a decision was made. For this project, the thermal comfort model proposed by (ISSO-publicatie 74, 2014) with (if necessary) extended running mean outdoor temperatures is used. As was explained before, the model is not fully suitable for this application and therefore the results should only be treated as an indication.

Table 20 Possible solutions for thermal comfort representation in the DST

No	Solution	Pros	Cons
1	ASHRAE 55 - analytical method	• Possibility to adjust clothing level and metabolic rate in a relatively wide range (0-1.5 clo and 1-2 met, respectively). • By the adjustments, the comfort zone in the psychrometric chart is relatively wide which seems to be proper for military conditions. • The model covers both heating and cooling season.	• The humidity ratio shown on the vertical axis of the psychrometric chart can be misleading to DST users because the humidity is not controlled in tents and also humidity is not such a recognizable thermal comfort factor as temperature.
2	ISSO 74 - the adaptive model used for the whole year	• The model is valid for both naturally ventilated and air-conditioned buildings. • The model covers both heating and cooling season. • It allows selecting the space class and thermal comfort requirements related to the class. • The required indoor temperature is presented as a function of running mean outdoor temperature which is more appealing to DST users. • The model is valid for clothing level 0.5-1 clo – for military winter conditions the clothing level is higher. The model can be adjusted by the use of the correction factor.	• The model is intended for the Dutch climate. Therefore, the model applies for running mean outdoor temperatures 5°C-22°C. The range is too narrow to cover various climates.
3	ISSO 74 - adaptive model with an extended running mean outdoor temperature to 38.5°C (based on (Manu, Shukla, Rawal, Thomas, & de Dear, 2016) used for the whole year	• The same as for No 2. • The extension of the upper limit of the mean running outdoor temperature allows covering hot climates.	• The extension of the upper limit of the mean running outdoor temperature does not comply with the guideline ISSO 74. • The lower mean running outdoor temperature limit is 5°C, which is too high for cold climates. (It can be extended by extrapolation of the horizontal lines shown in Figure 47, however, it will not comply with the guideline ISSO 74).
4	The use of lower and upper health risk operative temperatures of 12°C and 35°C (Tuladhar, Jahn, & Wasilowski Samuelson, 2019), respectively, instead of the use of a thermal comfort model	• Since any of the widely used thermal comfort models' assumptions are not suitable for military tents, the evaluation of the thermal comfort in tents cannot be done in a completely correct way. Another possibility is to evaluate the thermal condition in the tents based on health risk operative temperatures.	• There is no agreed-upon standard for health risk temperatures. • The health risk temperatures proposed by (Tuladhar, Jahn, & Wasilowski Samuelson, 2019) are intended for a vulnerable population, i.e. elderly, sick, and small children. • The DST user gets no information related to thermal comfort.
5	Graph showing the relation between the operative temperature and the air temperature	• The DST user gets information what are the operative temperatures in the tent when a given air temperature occurs. • The user can evaluate him/herself if thermal comfort can be always achieved. • There is no thermal comfort model involved and therefore misunderstandings related to the applicability of the models to a given situation are avoided.	• The DST user can find it problematic to interpret the graph. • No single value indicator (for example number of unmet hours) can be provided based on which the user can compare different cases.
6	Graph showing the relation between the mean radiant temperature and the air temperature	• The same as for No 5.	• The same as for No 5.

HEAT STRESS INDEX

Since the selected thermal comfort model (ISSO-publicatie 74, 2014) is not a perfect solution, it was decided to use also another indicator. Military missions, from the definition, are associated with extreme conditions. Therefore, it was decided to use a heat stress index which indicates if there is a risk of heat stress in certain thermal conditions.

The wet-bulb globe temperature index (WBGT) was invented during the 1950s to control the occurrence of heat illness in training camps of the USA Army and Marine Corps (Budd, 2008). It is currently the most widely used heat stress indicator described by (ISO 7243, 2003).

The WBGT is an empirical index combining the measurement of the natural wet-bulb temperature and the globe temperature together with the air temperature. Therefore, the index considers the main heat transfer mechanisms – evaporation, convection, and radiation, that affect the thermal sensation and strain. The WBGT is calculated from temperatures and therefore it is expressed in degree Celsius. However, the index should not be confused with "perceived" temperature. (d'Ambrosio Alfano, Malchaire, Palella, & Riccio, 2014)

The WBGT was calculated with the use of empirical equations explained by (Waclawek, 2013), (d'Ambrosio Alfano, Malchaire, Palella, & Riccio, 2014) and (Bernard, 1999) considering military clothes in the khaki color.

The standard (ISO 7243, 2003) provides reference values of the WBGT index (Table 21). The reference values are dependent on the metabolic rate and acclimatization.

Table 21 WBGT reference values according to ISO 7243

Metabolic rate [W/m2]	**WBGT reference value**	
	Acclimatized people (°C)	**Not acclimatized people(°C)**
Resting M < 65	33	32
65 < M < 130	30	29
130 < M < 200	28	26
200 < M < 260	25	22
M > 260	23	18

6 CONSIDERATIONS ON THE DECISION-SUPPORT TOOL STRUCTURE

The DST development options were explored keeping in mind the requirements mentioned in section 3.2. Three possible solutions were identified.

SOLUTION 1 – DATABASE OF MACHINE LEARNING PREDICTIONS

It is not feasible to perform EnergyPlus simulations for all possible cases defined by the user because of the necessary output storage space and time constraints. Therefore, the first solution is to simulate a limited number of cases and use a surrogate model to predict the remaining cases as it was done by (Papachristou, 2019) and (Aijazi, 2017). The surrogate model predictions are much faster than EnergyPlus simulations. Therefore, the database with results can be created within a reasonable time. The surrogate model can be created using machine learning. Machine learning techniques are a subset of artificial intelligence. The machine learning algorithm builds a model based on training data. After that, the model must be fine-tuned and validated using a separate dataset (testing data). Then the validated model can make predictions for data points not included in the training dataset. A scheme of solution 1 is shown in Figure 48. The pros and cons of the solution are listed in Table 22.

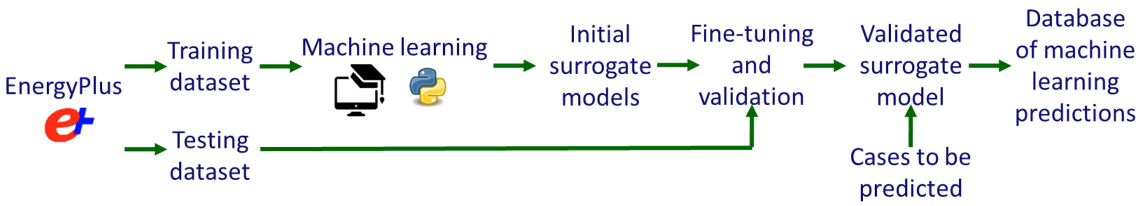


Figure 48 Scheme of solution 1

SOLUTION 2 – MACHINE LEARNING PREDICTION FOR A USER-DEFINED CASE

Figure 49 depicts a scheme of solution 2. The second solution is similar to the first one. The only difference is that in the second solution no database of machine learning predictions is generated. The prediction is made only for a case specified by the user. The user specifies the case via an interface, the surrogate model predict the results, and the results are presented to the user. The advantages and disadvantages of solution 2 are listed in Table 22.

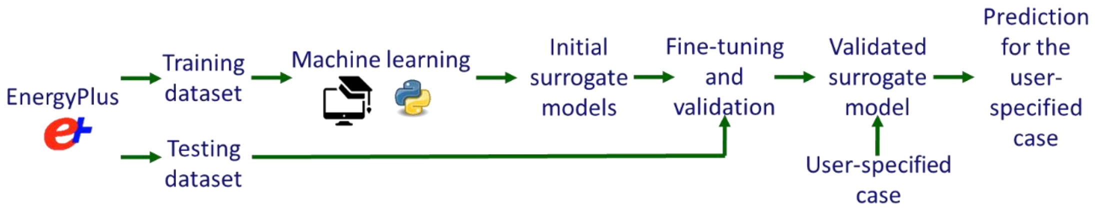


Figure 49 Scheme of solution 2

SOLUTION 3 – ENERGYPLUS SIMULATION RUN BY THE USER

The third solution is to allow the user to run the EnergyPlus simulation him/herself. A scheme of this solution is shown in Figure 50. The user specifies the case via a user-friendly interface, the input is preprocessed in Python, simulation input file (idf) is generated, EnergyPlus simulation is run, outputs are post-processed in Python, and the results are visualized and presented to the user. This approach involves no machine learning predictions. The pros and cons of the third solution are listed in Table 1.

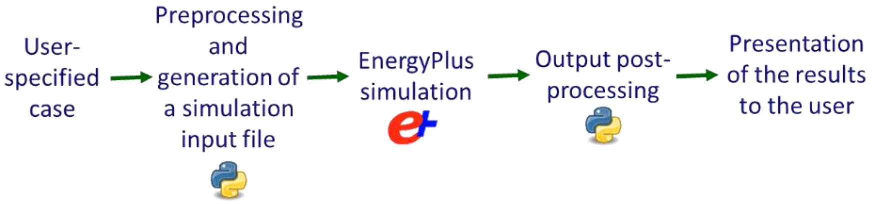


Figure 50 Scheme of solution 3

Table 22 Pros and cons of possible solutions for the DST development

Solution	**Pros**	**Cons**
Solution 1 – Database of machine learning predictions	+ Simple concept – user searches in a pre-calculated database	-Simulation and prediction time -A huge size of the database -Data filtering method -Limited customizability -Accuracy (a small number of training data points in comparison to predicted data points) -No prediction of time-series data -The E+ model must be fixed before testing of ML algorithms -No modifications of the tool inputs and outputs can be made later on
Solution 2 – Machine learning prediction for a user-defined case	+ Smaller size of the database (only simulated cases) + High customizability	-Simulation time -Accuracy (a small number of training data points in comparison to predicted data points) -No prediction of time-series data -The E+ model must be fixed before testing of ML algorithms -No modifications of the tool inputs and outputs can be made later on
Solution 3 – EnergyPlus simulation run by the user	+ Full customizability + Accuracy (no machine-learning predictions) + Small storage space necessary + Avoidance of time-consuming simulations + The E+ model can be adjusted until the end of the project if necessary + The tool inputs and outputs can be changed until the end of the project if necessary + Time-series outputs available	-Waiting-time for the user

Considering the pros and cons of the three solutions listed in Table 1 and the need for time series data, and keeping in mind the software installation restriction, it was decided to apply the third solution - EnergyPlus simulation run by the user. This solution makes use of Python and EnergyPlus. Both of them are portable – they can run out of the box on any machine with Windows system and the folders containing them can be saved in any location (local, network or removable drive). Therefore, the installation of Python and EnergyPlus is not necessary. An important advantage of solution 3 is that there is no machine learning prediction involved and therefore the results are not subjected to the machine-learning prediction error.

Solution 3 is modular – it is composed of four components: user input, user input processing, simulation input file generation, simulation run, and simulation output post-processing. The four components are interconnected however each of them can be modified in any stage of the project. This gives a lot of freedom and the possibility to make adjustments and improvements until the end of the project. For example, if The Ministry has some new ideas regarding the DST output, the simulation input file and the output post-processing components can be modified.

DST STRUCTURE

The final DST allows the user to run EnergyPlus simulation himself without interacting with the simulation engine directly. A simplified scheme of this solution is shown in Figure 51. A more detailed scheme is shown in Figure 52. The user specifies the case via a user input form in Excel, the input is preprocessed in Python, simulation input file (idf) is generated, EnergyPlus simulation is run, outputs are post-processed in Python, and the results are visualized and presented to the user as a PDF report. The whole DST is stored in one folder which is portable, can be stored in any location and can run out of the box.

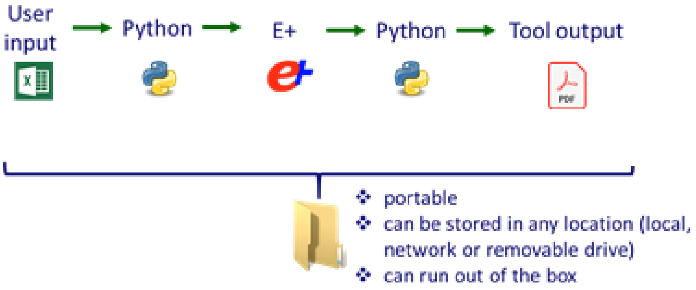


Figure 51 DST - simplified flow chart

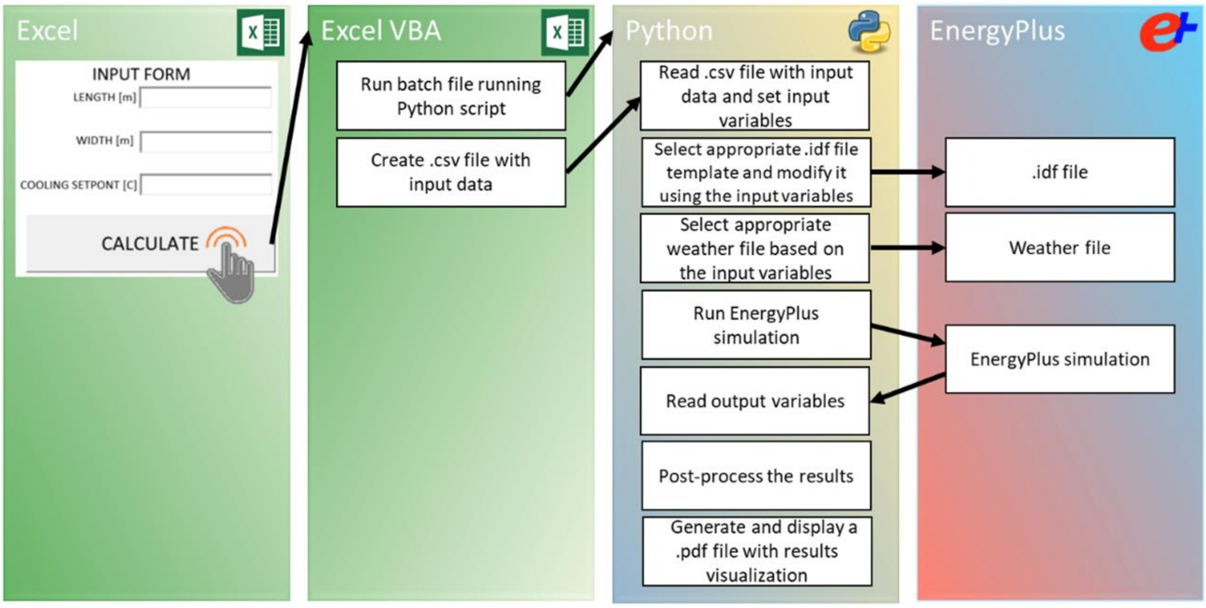


Figure 52 DST form - detailed scheme

7 DECISION-SUPPORT TOOL

7.1 TOOL DESCRIPTION

The final DST was designed and developed in such a way to ensure that the requirements of the client are met. The goal to develop a DST that is user-friendly, flexible, and reliable was achieved.

The DST was built on top of a well-known building performance simulation program. The program allows predicting what is going to happen in reality using a mathematical tent model which was created based on physical principles. The model considers the dynamic interactions between the tent, occupants, equipment, weather conditions, and the HVAC system. The applied modeling approach was supported by an extensive literature review, tests, and analysis described in section 5.

The DST was built on top of EnergyPlus that is a building performance simulation program. However, the user does not need to interact with the BPS model directly. The user workflow is very simple and is presented in Figure 53. First, the user needs to find and open the folder where the DST is stored. Then the DST input form can be open. The DST input form was developed in MS Excel. MS Excel is a software that the client is familiar with. Therefore, the fact that the input form is an MS Excel file is convenient for the client because there is no need to install or learn new software.

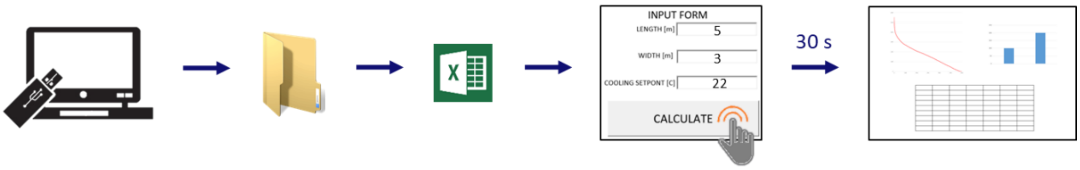


Figure 53 Final DST - flow chart – the DST user perspective

In the input form, the user can specify the tent location, characteristics, and intended usage. Next, the user can run the simulation directly from the Excel input form by one click. The possibility to run the simulation by the DST user provides large flexibility and enables the calculation of an unlimited number of possible cases. Furthermore, there are default settings in the input form which make it easier to fill the form in. Nevertheless, if the user wants to go beyond the default settings, the DST gives also the opportunity to insert user-defined materials' properties, which makes the DST even more flexible. The DST input form includes also short instructions explaining how to fill in each cell. If the user hovers the mouse over a cell, the instruction is displayed. If the user needs more information, he/she can click also on the "Help" button to display the DST user manual (see Appendix D, section 10.4).

After the calculations are done, a report in PDF format is displayed. The report includes information that is necessary to support the decision on the HVAC system size. It contains information about peak heating and cooling loads and also heating and cooling load duration curves. The load duration curve is the curve between the load (cooling or heating) and time in which the ordinates representing the load are in descending order. The user can learn from the curves what the consequences of the application of an HVAC system of a smaller capacity than the peak demand are. This way, the DST allows the user to make a risk-aware decision instead of deciding for the user. The load duration curves were created for the whole year and each season separately. It allows the user to adjust the HVAC system capacity to the season when the tent is intended to be used. If the user needs some explanation on how to extract valuable information from the load duration curves, he/she can read about it in the DST manual which can be opened by clicking on the “Help” button. Moreover, if the user clicks on the “How to understand load duration curves?” button, a video animation with the explanation will be displayed.

If the user wants to get information about energy demand, thermal comfort, or heat stress risk, he/she can open an additional output report by one click on the “Learn more” button in the MS Excel input form. Then, another report in the PDF format is displayed. The report shows the annual cooling and heating energy demand. Moreover, it indicates the percentage of uncomfortable hours during the whole year based on (ISSO-publicatie 74, 2014). The uncomfortable hours are also depicted in the thermal comfort chart to inform the user what the source of discomfort is – overheating or overcooling. However, it must be noted that the information about thermal comfort should be used only as an indication because the thermal comfort model used to assess the comfort in tents is not intended to be used for this kind of application. The reader is referred to section 5.3 for more information about thermal comfort models. Finally, the report shows also the heat stress index according to (ISO 7243, 2003) together with its reference values. The user can compare the calculated index to the reference values and can make sure that even if thermal discomfort may occur, there is no risk of heat stress. Again, if the user needs more explanation on how to interpret the results, he/she can learn more from the DST user manual.

All calculations are affected by numerous uncertainties, mainly related to materials’ properties and infiltration intensity. The uncertainties are inevitable. Therefore, to ensure the reliability of the DST, all results are presented as ranges. The lower and upper boundaries of the ranges were calculated assuming the most maximum and minimum values of certain parameters. The reader is referred to section 5.2.6 for more information about the uncertainties.

The features of the DST contributing to its user-friendliness, flexibility, and reliability are summarized in Table 23.

The main function of the DST is the sizing of HVAC systems for tents. However, it also demonstrates the effects of weather conditions, tents’ properties, and shading applications on the thermal comfort and heat stress risk in tents.

Table 23 Summary of the DST features making it user-friendly, flexible, and reliable

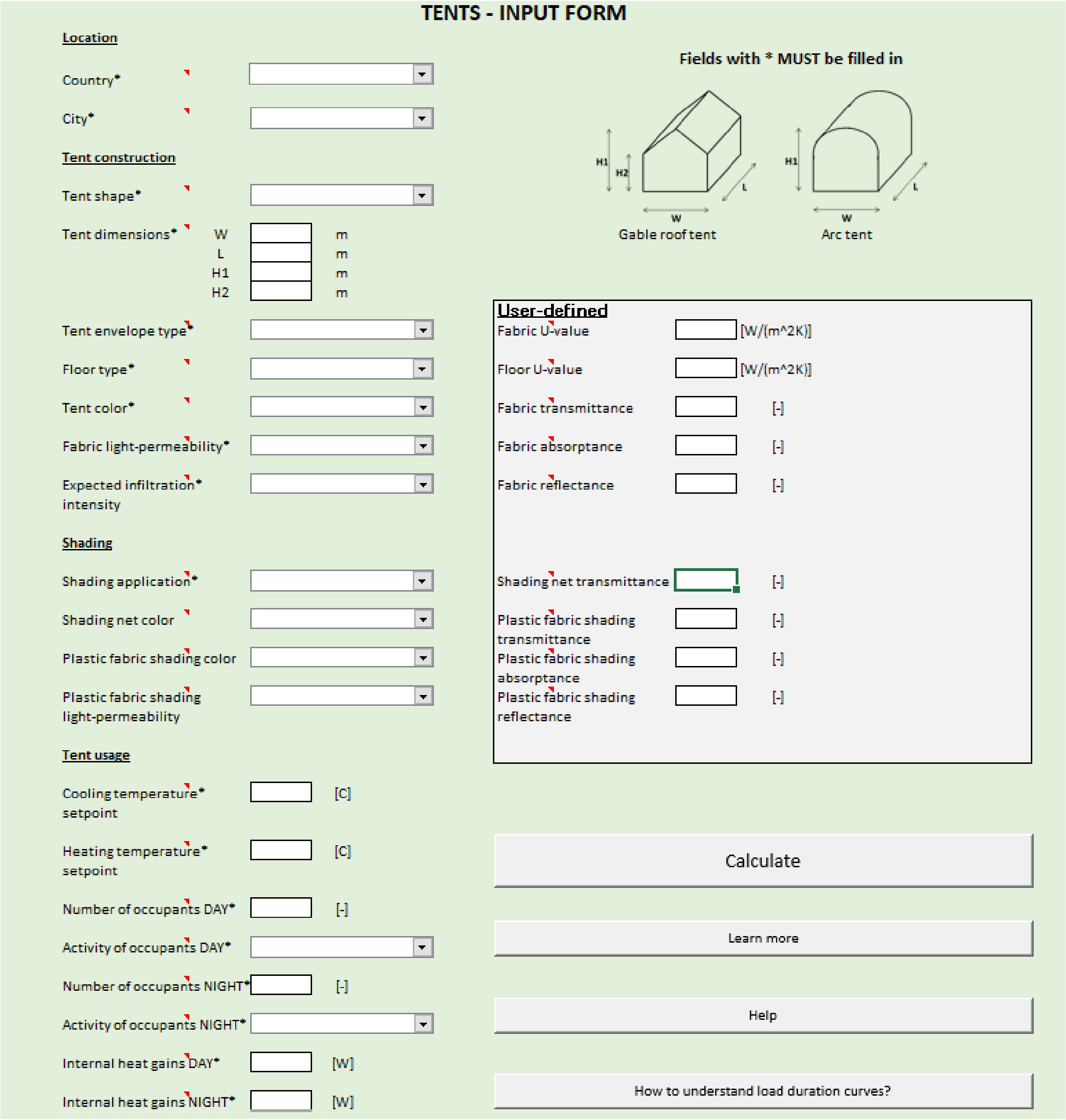
User-friendliness	- Input form in MS Excel which the user is familiar with - There is no need to install and learn new software - The whole DST can be operated from the input form - The user does not need to know any programming language and interact with the simulation directly - The input form is clear and is protected against changes which could cause malfunctioning of the DST - The input form includes defaults - The user can specify non-numeric settings using a dropdown menu - The user can specify numeric settings by typing values - There are short instructions in the input form explaining how to fill in each cell - There is the "Help" button which displays the DST user manual - There is the "How to understand load duration curves?" button which displays the animated explanation of load duration curves - The DST generate reports in the PDF format which can be open on any computer and other devices - The reports are saved so the user can come back to them - The information necessary for sizing and the additional information are included in separate reports so that the user is not confused by a large amount of information - The HVAC system size can be adjusted to the season when the tent is used
Flexibility	- The possibility to perform calculations for an unlimited number of possible cases - The opportunity to insert user-defined materials' properties instead of using the default settings - The DST is future-proof, it can be used for tents currently owned by the Dutch army as well as tents that will be bought in the future
Reliability	- The DST is built on top of a well-known and reliable building performance simulation program EnergyPlus - The applied modeling approach is based on informed assumptions supported by extensive literature review, tests, and analysis - Results are provided in ranges reflecting the inevitable uncertainty of the simulation inputs

7.2 USER INPUTS

The DST input form is shown in Figure 54. The form is divided into two parts – green and grey. The input cells in the green part must be filled in, otherwise, the DST does not work. On the other hand, the grey part is not compulsory. It contains additional inputs and can be used if the default settings from the green part are not representative or if the user has detailed information about the materials' properties which can be used to get more accurate advice.

There are also four buttons included in the form. The "Calculate" button runs the EnergyPlus simulation and displays the output report providing information necessary for HVAC systems sizing. The "Learn more" button displays the additional output report containing the information about cooling and heating energy demand, thermal comfort, and heat stress risk. The "Help" button opens the DST user manual. Finally, the "How to understand load duration curves?" button displays an animation explaining load duration curves.

Detailed descriptions and explanations of the user inputs can be found in the DST user manual (see Appendix D, section 10.4).



TENTS - INPUT FORM

Fields with * MUST be filled in

Location

Country*

City*

Tent construction

Tent shape*

Tent dimensions* W m
L m
H1 m
H2 m

Tent envelope type*

Floor type*

Tent color*

Fabric light-permeability*

Expected infiltration* intensity

Shading

Shading application*

Shading net color

Plastic fabric shading color

Plastic fabric shading light-permeability

Tent usage

Cooling temperature* setpoint [C]

Heating temperature* setpoint [C]

Number of occupants DAY* [-]

Activity of occupants DAY*

Number of occupants NIGHT* [-]

Activity of occupants NIGHT*

Internal heat gains DAY* [W]

Internal heat gains NIGHT* [W]

User-defined

Fabric U-value [W/(m^2K)]

Floor U-value [W/(m^2K)]

Fabric transmittance [-]

Fabric absorptance [-]

Fabric reflectance [-]

Shading net transmittance [-]

Plastic fabric shading transmittance [-]

Plastic fabric shading absorptance [-]

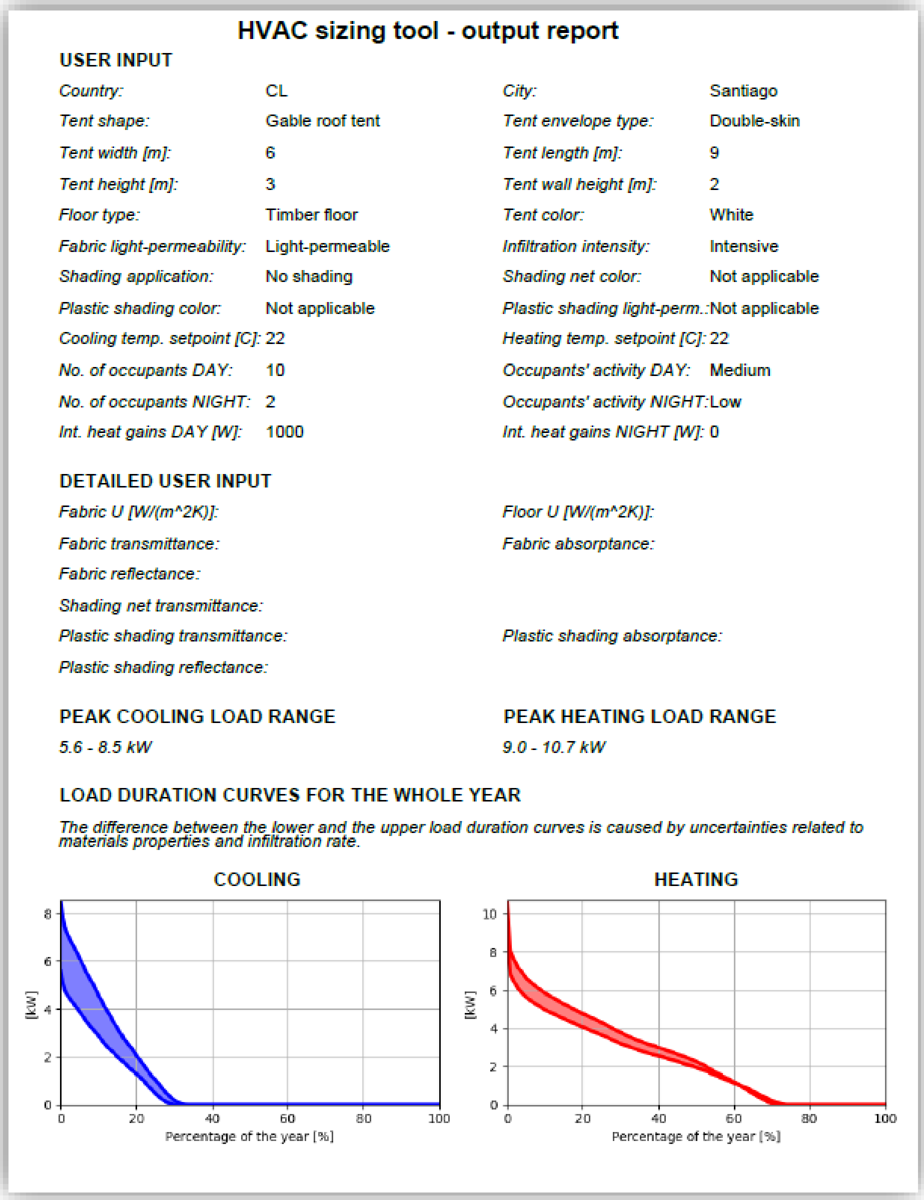
Plastic fabric shading reflectance [-]

Figure 54 The DST input form

7.3 DST OUTPUTS

As it was explained in section 7.1, the DST generates two output reports in PDF format – the basic one (containing information necessary for the HVAC system sizing) and the additional one (including information regarding heating and cooling energy demand, thermal comfort, and heat stress risk). The output information was divided into two parts on the request of the client because the additional information is often not needed.

Figure 55 and Figure 56 show an example of the basic output report. The first two sections of the output report present the user settings. It enables the user to easily recognize the report and go back to it if necessary without the necessity to perform the calculations once again. The third section contains information about the annual peak heating and cooling loads. The fourth section shows the heating and cooling load duration curves. The information about the peak heating and cooling loads and the load duration curves allow the user to make an informed, risk-aware decision on the HVAC system size. The last section of the report presents heating and cooling load duration curves for each season. The provided information can be used to size the HVAC system for a tent that is intended to be used for a shorter period than the whole year and to adjust the system capacity to the weather conditions corresponding to a specific season. For more information on how to interpret the information provided in the report, please see the user manual (Appendix D, section 10.4).



HVAC sizing tool - output report

USER INPUT

Country:	CL	*City:*	Santiago
Tent shape:	Gable roof tent	*Tent envelope type:*	Double-skin
Tent width [m]:	6	*Tent length [m]:*	9
Tent height [m]:	3	*Tent wall height [m]:*	2
Floor type:	Timber floor	*Tent color:*	White
Fabric light-permeability:	Light-permeable	*Infiltration intensity:*	Intensive
Shading application:	No shading	*Shading net color:*	Not applicable
Plastic shading color:	Not applicable	*Plastic shading light-perm.:*	Not applicable
Cooling temp. setpoint [C]:	22	*Heating temp. setpoint [C]:*	22
No. of occupants DAY:	10	*Occupants' activity DAY:*	Medium
No. of occupants NIGHT:	2	*Occupants' activity NIGHT:*	Low
Int. heat gains DAY [W]:	1000	*Int. heat gains NIGHT [W]:*	0

DETAILED USER INPUT

Fabric U [W/(m^2K)]:	*Floor U [W/(m^2K)]:*
Fabric transmittance:	*Fabric absorptance:*
Fabric reflectance:	
Shading net transmittance:	
Plastic shading transmittance:	*Plastic shading absorptance:*
Plastic shading reflectance:	

PEAK COOLING LOAD RANGE

5.6 - 8.5 kW

PEAK HEATING LOAD RANGE

9.0 - 10.7 kW

LOAD DURATION CURVES FOR THE WHOLE YEAR

The difference between the lower and the upper load duration curves is caused by uncertainties related to materials properties and infiltration rate.

Figure 55 Output report containing information necessary for the HVAC system sizing, page 1

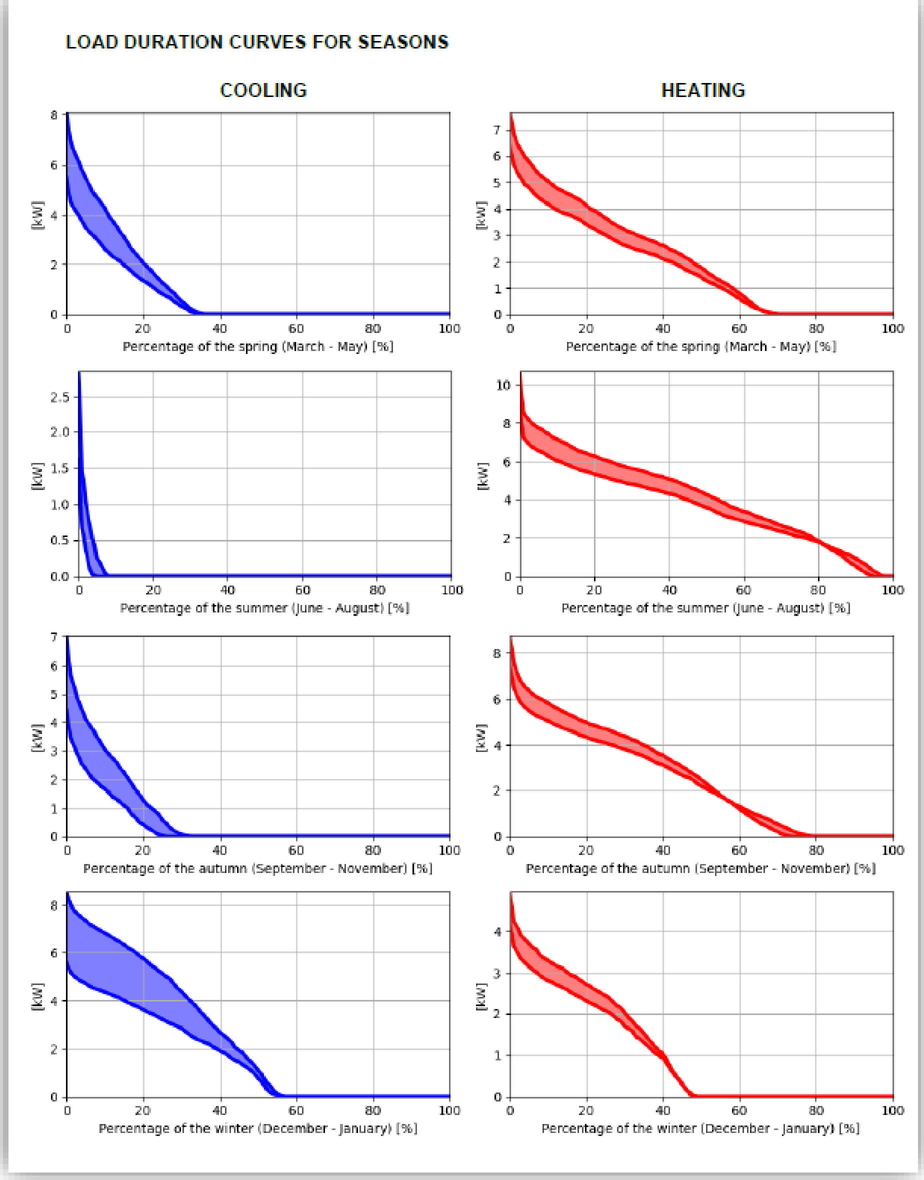
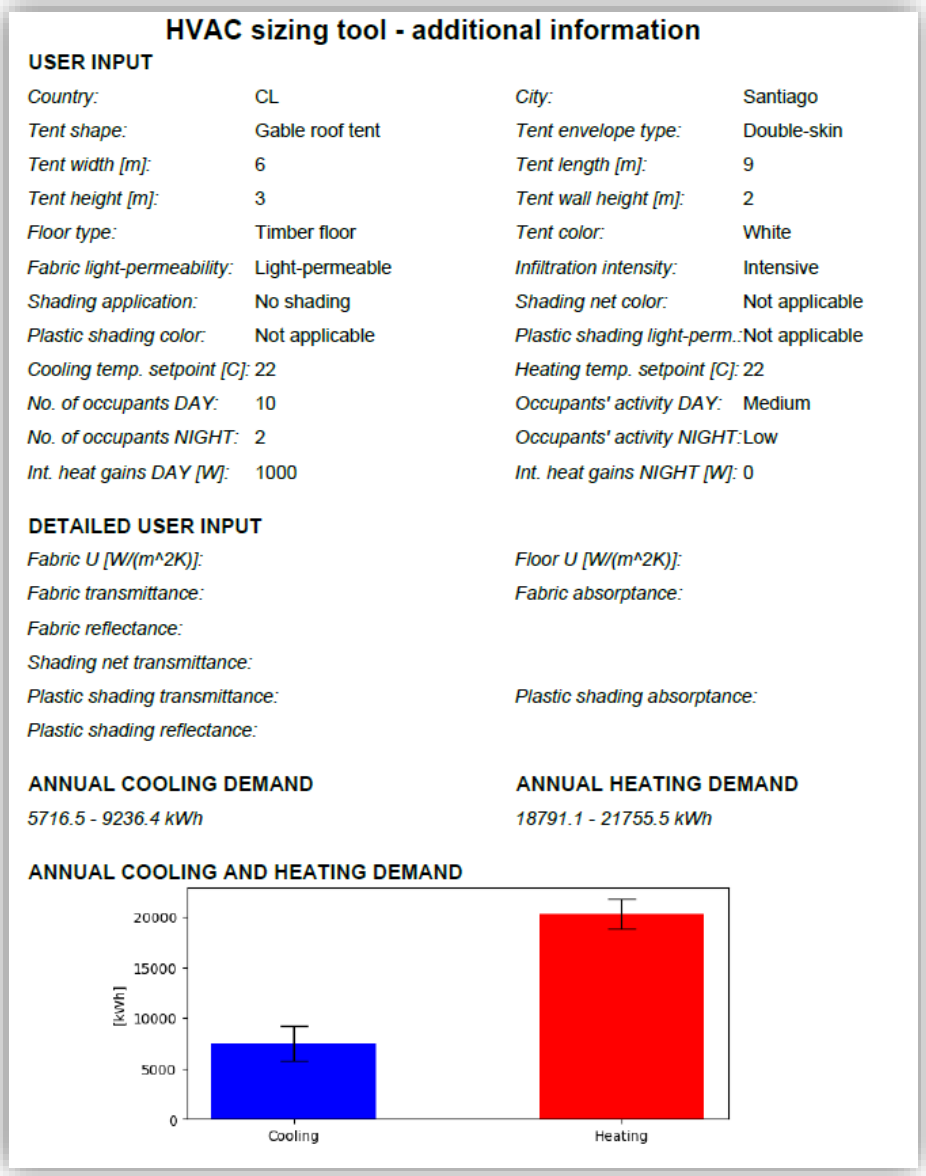


Figure 56 Output report containing information necessary for the HVAC system sizing, page 2

Figure 57 and Figure 58 present the additional output report. Again, the first two sections of the report contain the input information. The third and fourth sections show the annual heating and cooling energy demand. It must be noted that the presented demand does not reflect directly the energy demand of the HVAC system. The numbers reflect the amount of thermal energy necessary to keep the indoor temperature within the range determined by the DST user. The final energy demand is dependent on the HVAC system efficiency and distribution losses which in this case are difficult to predict. The fifth and sixth sections provide information about thermal comfort according to (ISSO-publicatie 74, 2014). Thermal comfort is not only dependent on the air temperature but also the radiant temperature which is related to the temperature of surrounding objects. Due to the low thermal resistance of the tent envelope, its internal surface temperature is strongly affected by the outdoor environment conditions. Therefore, even if the required air temperature in the tent is maintained, thermal discomfort may occur due to a high or low temperature of the tent envelope.

The last part of the report shows the WBGT heat stress index indicating if there is a heat stress danger in the tent. For more information on how to interpret the information provided in the report, please see the user manual (Appendix D, section 10.4).

Subsections 7.4 and 7.5 describe two use cases explaining how the information provided by the DST can be used.



HVAC sizing tool - additional information

USER INPUT

Country:	CL	*City:*	Santiago
Tent shape:	Gable roof tent	*Tent envelope type:*	Double-skin
Tent width [m]:	6	*Tent length [m]:*	9
Tent height [m]:	3	*Tent wall height [m]:*	2
Floor type:	Timber floor	*Tent color:*	White
Fabric light-permeability:	Light-permeable	*Infiltration intensity:*	Intensive
Shading application:	No shading	*Shading net color:*	Not applicable
Plastic shading color:	Not applicable	*Plastic shading light-perm.:*	Not applicable
Cooling temp. setpoint [C]:	22	*Heating temp. setpoint [C]:*	22
No. of occupants DAY:	10	*Occupants' activity DAY:*	Medium
No. of occupants NIGHT:	2	*Occupants' activity NIGHT:*	Low
Int. heat gains DAY [W]:	1000	*Int. heat gains NIGHT [W]:*	0

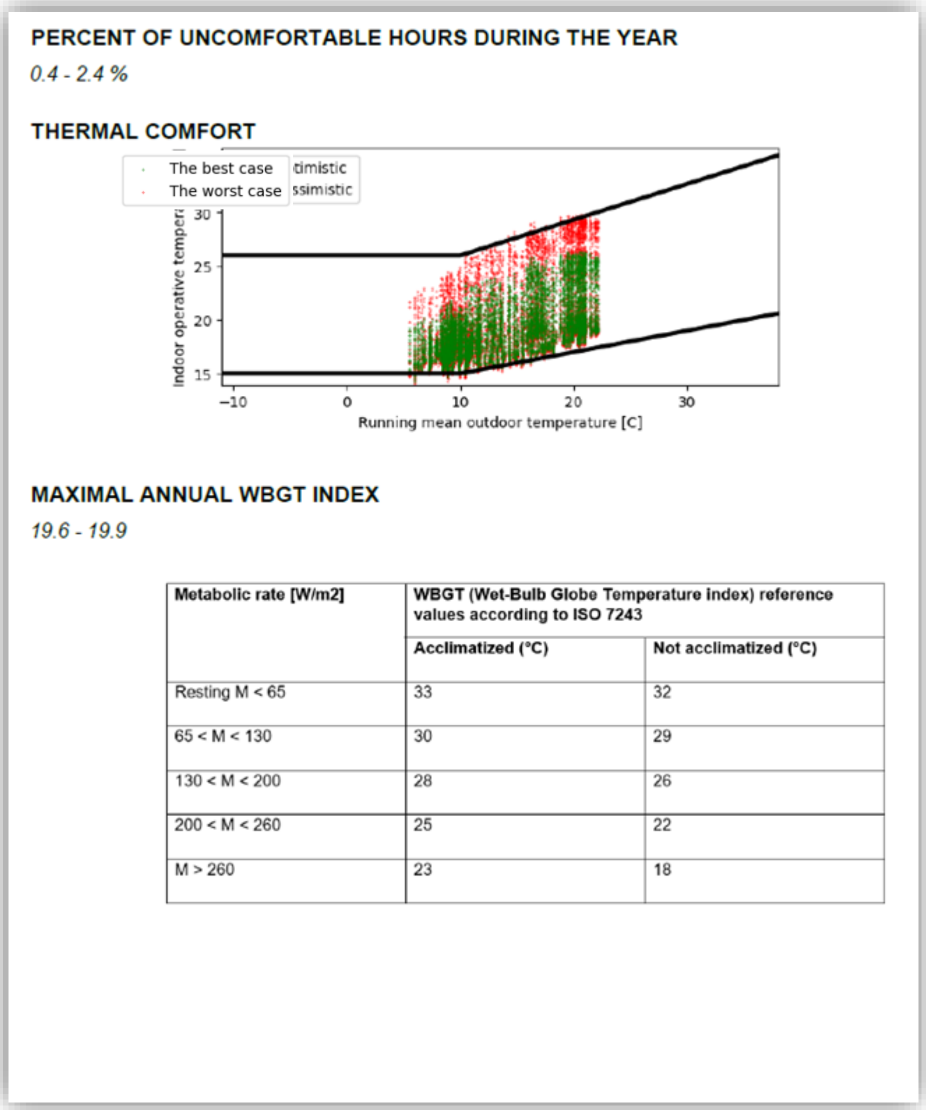
DETAILED USER INPUT

Fabric U [W/(m^2K)]:		*Floor U [W/(m^2K)]:*	
Fabric transmittance:		*Fabric absorptance:*	
Fabric reflectance:			
Shading net transmittance:			
Plastic shading transmittance:		*Plastic shading absorptance:*	
Plastic shading reflectance:			

ANNUAL COOLING DEMAND	ANNUAL HEATING DEMAND
5716.5 - 9236.4 kWh	*18791.1 - 21755.5 kWh*

ANNUAL COOLING AND HEATING DEMAND

Figure 57 Output report containing additional information, page 1



PERCENT OF UNCOMFORTABLE HOURS DURING THE YEAR

0.4 - 2.4 %

THERMAL COMFORT

MAXIMAL ANNUAL WBGT INDEX

19.6 - 19.9

Metabolic rate [W/m2]	WBGT (Wet-Bulb Globe Temperature index) reference values according to ISO 7243	
	Acclimatized (°C)	Not acclimatized (°C)
Resting M < 65	33	32
65 < M < 130	30	29
130 < M < 200	28	26
200 < M < 260	25	22
M > 260	23	18

Figure 58 Output report containing additional information, page 2

7.4 USE CASE 1

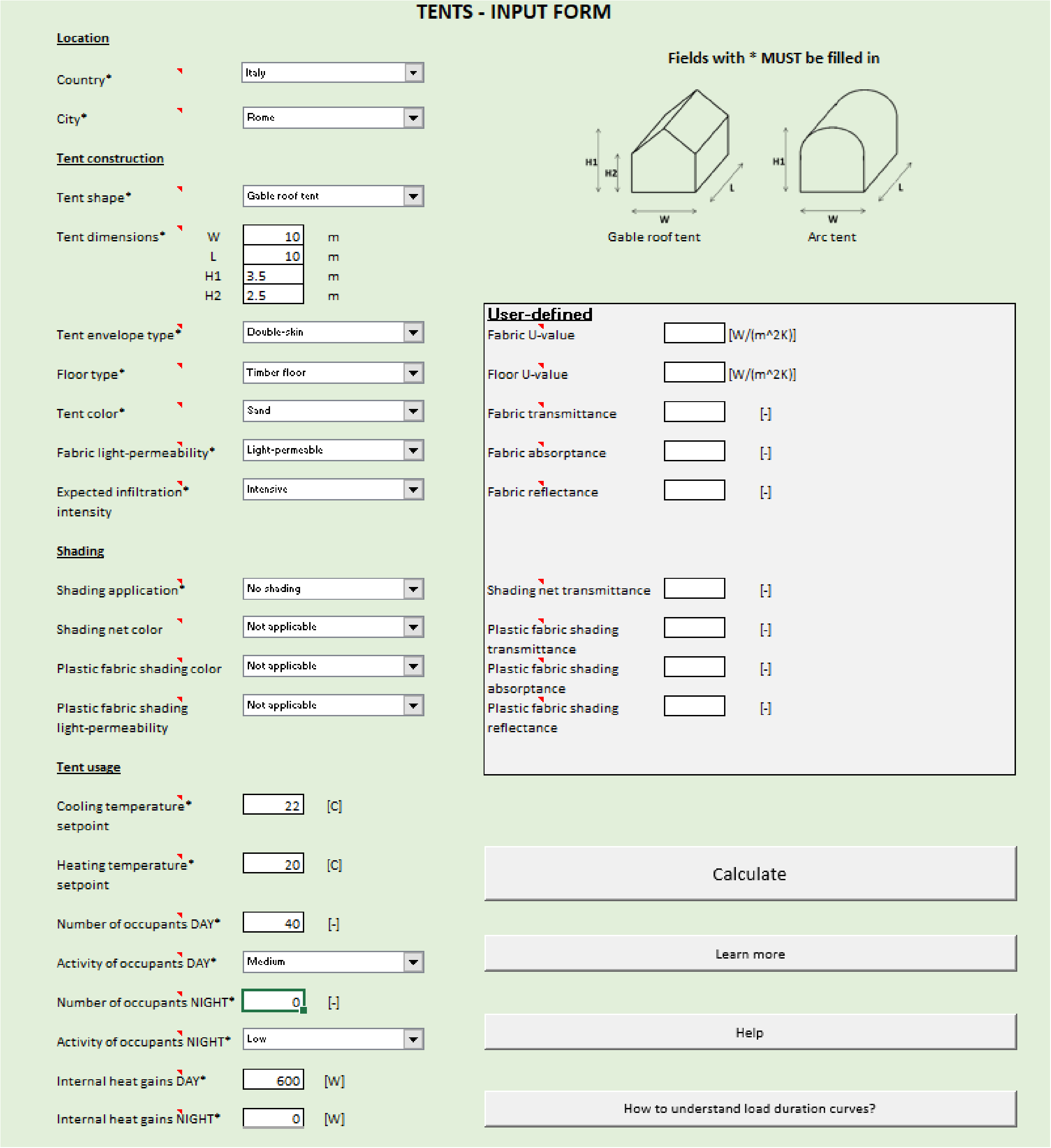
SITUATION DESCRIPTION

The DST user is organizing military training in Italy in the summertime. He is planning to arrange a sand-colored, double-skin, 10 m wide, 10 m long, and 3.5 m high tent as a canteen. The tent is not going to be shaded. The canteen will be occupied only during the daytime and will host 40 soldiers at once. There are no other heat sources in the tent – only the soldiers and their meals. The DST user wants to know what cooling capacity is necessary.

SOLUTION

The DST user fills in the input form as can be seen in Figure 59 and clicks the “Calculate” button. After that, the output report is displayed. Since the training is organized in summer, the user checks the load duration curves for the summer (Figure 60). The DST user has an air-conditioning unit of 18 kW in the stock and he wants to check if this capacity is enough. Considering the most pessimistic scenario, the summer peak cooling load is 26 kW and the application of an air-conditioner of 18 kW would result in about 15% risk of overheating. It means that during about 15% of the summertime, the required indoor air temperature would not be met. On the other hand, considering the most optimistic scenario, the 18 kW air-conditioner is just enough to meet the requirements. The DST user wants to avoid complaints and to provide comfortable eating conditions. Therefore, he decides to provide a 26 kW air-conditioning unit.

The user notices that the tent also requires some heating. He knows that in general higher heating needs occur at night due to the lack of solar radiation. Moreover, heating is necessary for only about 20% of the summertime. He concludes that the heating needs probably occur at night when the tent is not occupied. Therefore, he is not going to provide any heating device.



TENTS - INPUT FORM

Fields with * MUST be filled in

Location

Country*: Italy
City*: Rome

Tent construction

Tent shape*: Gable roof tent
Tent dimensions*: W 10 m; L 10 m; H1 3.5 m; H2 2.5 m
Tent envelope type*: Double-skin
Floor type*: Timber floor
Tent color*: Sand
Fabric light-permeability*: Light-permeable
Expected infiltration* intensity: Intensive

Shading

Shading application*: No shading
Shading net color: Not applicable
Plastic fabric shading color: Not applicable
Plastic fabric shading light-permeability: Not applicable

Tent usage

Cooling temperature* setpoint: 22 [C]
Heating temperature* setpoint: 20 [C]
Number of occupants DAY*: 40 [-]
Activity of occupants DAY*: Medium
Number of occupants NIGHT*: 0 [-]
Activity of occupants NIGHT*: Low
Internal heat gains DAY*: 600 [W]
Internal heat gains NIGHT*: 0 [W]

User-defined

Fabric U-value: [W/(m^2K)]
Floor U-value: [W/(m^2K)]
Fabric transmittance: [-]
Fabric absorptance: [-]
Fabric reflectance: [-]
Shading net transmittance: [-]
Plastic fabric shading transmittance: [-]
Plastic fabric shading absorptance: [-]
Plastic fabric shading reflectance: [-]

Figure 59 DST input form - Use case 1

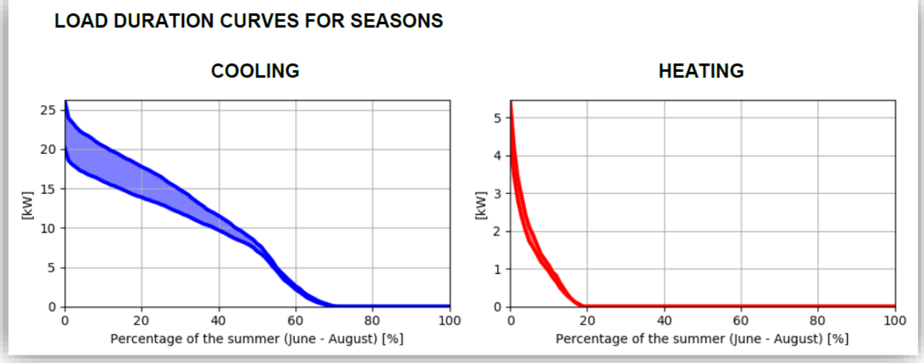


Figure 60 Load duration curves for the summer - Use case 1

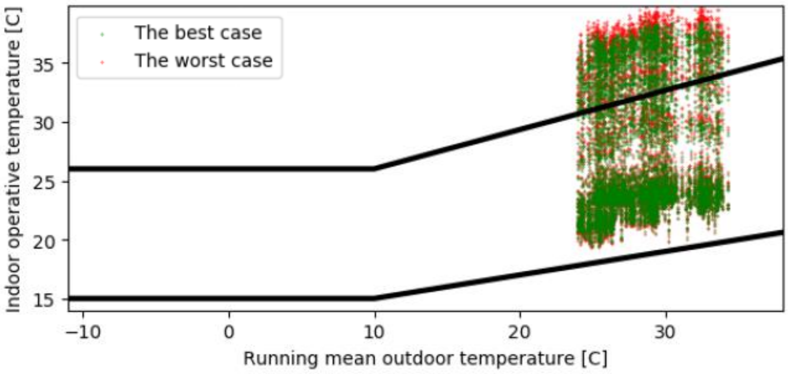
7.5 USE CASE 2

SITUATION DESCRIPTION

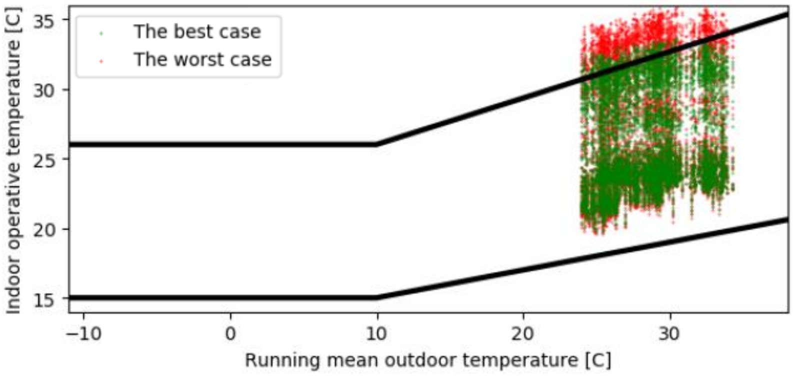
A green, double-skin, 5 m wide, 11 m long, and 4.5 m high tent is being used in Burkina Faso as a relaxation room. Together with the tent, a black shading net was delivered. However, this net was not installed. After some time, the person who delivered the tent together with an air-conditioning unit gets a complaint that the capacity of the air-conditioner is too low and that it is too hot in the tent.

SOLUTION

The person who delivered the tent replies to the complaining person that the tent was provided with a shading net which should be installed. This way, the cooling load of the tent will be reduced and the air-conditioner capacity will be enough. Moreover, he demonstrates also the positive impact of the shading on the thermal comfort by showing the thermal comfort charts presented in Figure 61. The charts prove that the discomfort caused by the high temperature of the tent envelope can be reduced by the shading. Moreover, the graphs also show that due to the extremely hot climate in Burkina Faso and the low thermal resistance of the tent envelope, discomfort may occur even if the tent is equipped with the shading and an air-conditioning system of appropriate capacity.



No shading



Net shading

Figure 61 Impact of shading on the thermal comfort - Use case 2

8 CONCLUDING REMARKS

8.1 FINAL DECISION-SUPPORT TOOL

The main purpose of this project was to help the decision-makers from the Dutch army in HVAC systems sizing for military tents. This goal was achieved by the development of the DST which allows the decision-makers to make informed, risk-aware decisions.

An important part of this project was the requirements specification process. Interviews with the representatives from the Defense Organization provided a lot of information allowing the understanding of the current situation and problems regarding the decision-making on the HVAC systems' capacity for tents. The applied requirements specification techniques – the creation of personas and writing user stories – helped to organize the obtained information and to translate it into a list of requirements. The defined requirements were validated with the client using the look-up table which was created for the most common scenarios of tents use. When specifying the requirements for the DST, it became clear that the DST to be delivered at the end of this project should be user-friendly, flexible, and reliable.

The whole DST can be operated from the intuitive input form that is developed in MS Excel. MS Excel is software the user is familiar with. Therefore, no specialist knowledge of BPS and programming languages is needed. Moreover, the input form includes default settings and user support. The results are displayed as coherent reports in PDF format and therefore, they can be saved and opened on any computer and other devices. The outputs from the DST are divided into two parts allowing the user to choose which piece of information he wants to see and avoiding the risk of confusion caused by an unnecessarily large amount of information. All these features make the DST user-friendly.

Because the DST is not a database and it allows the user to run the building performance simulation himself without the necessity to interact with the simulation engine directly, calculations for an unlimited number of possible cases can be performed. This is possible because the simulation time for a tent is relatively short. This approach could not be applied for a complex building because the calculation time would be significantly longer and not acceptable for the DST user. The DST input form contains a lot of default settings to facilitate the use of the DST. However, instead of using the default settings, the user can specify some physical properties of the tent himself. This way, the scope of the DST is not limited by the defaults. These possibilities make the DST flexible and future-proof. The DST can be used for the tents used by the Dutch army now as well as purchased in the future.

The DST was created on top of a well-known and reliable building performance simulation program. The modeling approach was defined based on informed assumptions supported by extensive research described in this report. To ensure reliability, the impact of inevitable uncertainties is reflected in the fact that results are presented with uncertainty ranges.

The DST meets the established requirements and provides the user with information supporting the decision-making on HVAC systems' capacity for military tents. It shows the peak heating and cooling needs, but it also demonstrates the effect of the application of lower-capacity heating and cooling units. Moreover, it allows adjusting the capacity to the season when the tent is to be used. It also provides information about the annual heating and cooling energy demand. Furthermore, the DST provides insights into thermal comfort and heat stress risk in tents. This information helps the user to understand the effects of the tent features and shading application on the thermal comfort of the occupants. This knowledge can support decisions on which tents should be used for which applications. It can also influence the choice of newly purchased tents. Moreover, the information about the causes of thermal discomfort in the tents can be shared with the tents' occupants. Having this knowledge, they can undertake some measures to mitigate the impacts of extreme weather conditions on the thermal performance of the tents. However, sometimes, if the weather conditions are very extreme, it is not possible to achieve thermal comfort in such a light-weight and badly-insulated temporary structure. The knowledge about the reason for the discomfort can make it easier for the occupants to accept this situation.

Meeting the main requirements for the DST – that it should be user-friendly, flexible, and reliable – provided the main challenge of this project. However, thanks to extensive analysis, tests, and literature review, a solution was found that strikes a right balance between these three characteristics. The DST that is delivered to the stakeholders has thus met all these established requirements.

8.2 LIMITATIONS AND FUTURE WORK

While the stakeholder objectives have been met with this DST, from a design engineer point of view, there are a number of limitations that are worth noting here. The limitations of the DST which are difficult to solve are discussed below:

- Impacts of precipitation, tents' leakages, need for clothes drying, and the resulting increase in the humidity level are not considered in this study. It is difficult to estimate how a user-defined tent withstands precipitation because it depends on the tent's construction, materials, and also how carefully it is assembled. Modeling of these aspects would be complex and very uncertain.
- The DST does not consider the tent orientation and shading caused by external objects because anyway, the DST user is not able to predict these conditions.
- The DST considers that the heated and cooled air is fully recirculated and the fresh air is provided via natural ventilation and infiltration. This assumption was made in consultation with the client assuming that during the peak demand the HVAC system is used in the most efficient way, namely in the recirculation mode. This assumption was made to avoid significant oversizing of the system. If worst-case assumptions would be made for all aspects, the risk would be lowered, but in many cases the system would be significantly oversized. That would question the usefulness and existence of the simulation-based DST because the decision-makers could just size the equipment based on previous experiences using a large safety factor. Nevertheless, the goal of the decision-makers is to avoid both under- and oversizing of the HVAC systems. The consequence of undersizing is that the setpoint temperature is not reached. However, there are also negative consequences of oversized systems, namely noisy and unstable operation, lower efficiency, and higher costs.
- The uncertainty related to occupancy, occupants' behavior, and internal heat gains is not taken into account because otherwise, it would make the DST outputs very uncertain and therefore not meaningful for the user. The settings for these parameters are prescriptive and quite limited since more detailed occupancy profiles are not known by the DST user.
- The thermal comfort model used in the DST is based on the standard (ISSO-publicatie 74, 2014). The model was certainly not developed to be used for military tents. Its limitations are

described in section 5.3. Therefore, the results should not be treated literally but just as a helpful indication. So far, no thermal comfort model for tents was developed. Moreover, thermal comfort calculations are done for the whole year - it is assumed that the tent is occupied all the time. In reality, this is not the case, however, the DST user is not able to predict the tent occupancy schedule in more detail.

- The heating and cooling load and the annual cooling and heating energy demand are calculated with the assumption that the HVAC system keeps the required temperature all the time. Moreover, it must be noted that the numbers reflect the thermal energy required to keep the indoor temperature on the desired level. Therefore, if the HVAC system has a lower efficiency than the manufacturer assessed or if there are significant distribution losses, the capacity calculated by the DST can be underestimated. Also, the heating and cooling demand do not directly reflect the fuel or electricity demand which is affected also by the system efficiency, distribution losses, and fans' energy consumption. The effect of these factors is difficult to assess.

Even though there are limitations with no solutions, a number of limitations can be potentially solved:

- All calculations are done with the TMY weather data (typical meteorological year) as boundary conditions. The TMY is a compilation of hourly weather data for a given location for a one year period. The data is selected from data collected in a longer period. For each month the data is selected from the year that is treated as the most typical for that month. Therefore, the impact of climate change and extreme weather events is not taken into account. The DST could be extended with calculations taking into account these effects. Moreover, the weather data is collected by meteorological stations which are often located nearby cities and airports. Therefore, weather information for areas distant from cities is usually not available. Additional functionality that enables the user to use self-collected weather data could be added to the DST in order to overcome this limitation.
- It is assumed that the tent fabric’s transmittance, absorptance, and reflectance are constant for the whole solar radiation spectrum. This simplification could be avoided if detailed data about these materials’ properties would be available.
- The DST includes two typical tent shapes, namely gable roof tent, and arc tent. The addition of non-standard shapes requires the addition of new simulation file templates and modification of the code.
- In the future, the DST could potentially be used also for non-military purposes, for example for festivals or different open-air events.

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10 APPENDICES

10.1 APPENDIX A - LOOK-UP TABLE - MANUAL

Tool for decision-making on HVAC systems' capacity for military tents

Look-up table - Manual

INTRODUCTION

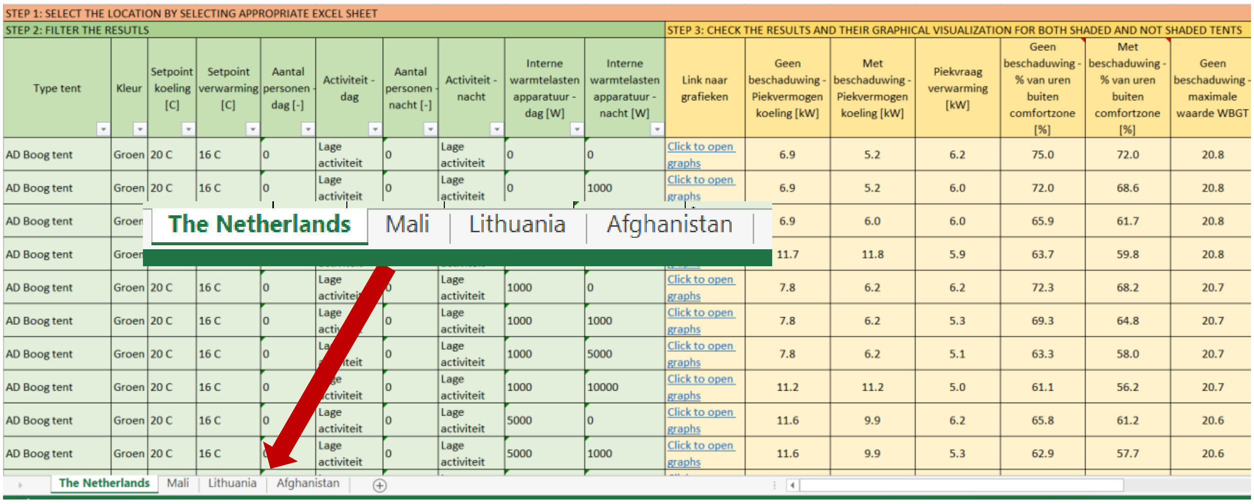
The look-up table is a mean to facilitate communication with the client. The goal of the look-up table delivery is to check with the client the tool's inputs and outputs, to receive feedback regarding the validity of results, and to determine additional features of the DST which are required. The look-up table is an Excel sheet with results filtering possibility and with hyperlinks to graphs. The look-up table was created for eight predefined tent types, whose specifications were provided by the client, considering four relevant locations. This manual explain how to use the look-up table and how to read the outputs.

USER INPUTS

After opening the 'Look-up table.xlsx' file, the user needs to take three steps.

STEP 1: SELECT THE LOCATION BY SELECTING APPROPRIATE EXCEL SHEET

The first step is to select one of four available locations (The Netherlands, Mali, Lithuania or Afghanistan). This can be done by selecting the appropriate Excel sheet at the bottom of the screen (Figure 62).



STEP 1: SELECT THE LOCATION BY SELECTING APPROPRIATE EXCEL SHEET

STEP 2: FILTER THE RESUTLS

STEP 3: CHECK THE RESULTS AND THEIR GRAPHICAL VISUALIZATION FOR BOTH SHADED AND NOT SHADED TENTS

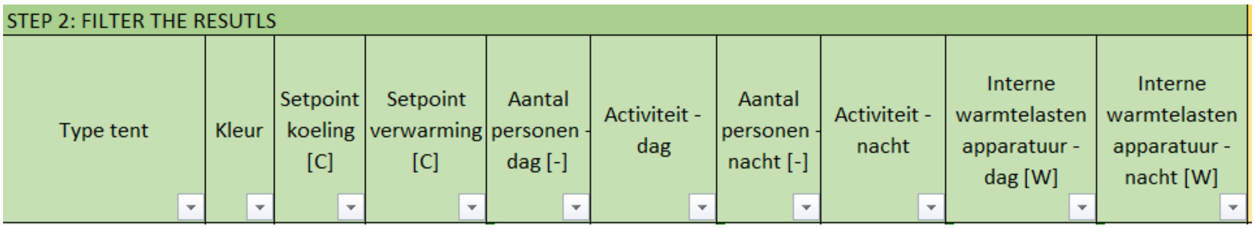
Type tent	Kleur	Setpoint koeling [C]	Setpoint verwarming [C]	Aantal personen - dag [-]	Activiteit - dag	Aantal personen - nacht [-]	Activiteit - nacht	Interne warmtelasten apparatuur - dag [W]	Interne warmtelasten apparatuur - nacht [W]	Link naar grafieken	Geen beschaduwing - Piekvermogen koeling [kW]	Met beschaduwing - Piekvermogen koeling [kW]	Piekvraag verwarming [kW]	Geen beschaduwing - % van uren buiten comfortzone [%]	Met beschaduwing - % van uren buiten comfortzone [%]	Geen beschaduwing - maximale waarde WBGT
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	0	0	Click to open graphs	6.9	5.2	6.2	75.0	72.0	20.8
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	0	1000	Click to open graphs	6.9	5.2	6.0	72.0	68.6	20.8
AD Boog tent	Groe										6.9	6.0	6.0	65.9	61.7	20.8
AD Boog tent	Groe										11.7	11.8	5.9	63.7	59.8	20.8
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	1000	0	Click to open graphs	7.8	6.2	6.2	72.3	68.2	20.7
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	1000	1000	Click to open graphs	7.8	6.2	5.3	69.3	64.8	20.7
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	1000	5000	Click to open graphs	7.8	6.2	5.1	63.3	58.0	20.7
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	1000	10000	Click to open graphs	11.2	11.2	5.0	61.1	56.2	20.7
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	5000	0	Click to open graphs	11.6	9.9	6.2	65.8	61.2	20.6
AD Boog tent	Groen	20 C	16 C	0	Lage activiteit	0	Lage activiteit	5000	1000	Click to open graphs	11.6	9.9	5.3	62.9	57.7	20.6

Figure 62 Location selection

STEP 2: FILTER THE RESULTS

The second step is to filter the results. In order to do this, the user needs to use filters shown in Figure 63. The filters are in the green part of the look-up table. After clicking on one of the white boxes with the arrow, the user can select the desired option as can be seen in Figure 64. The user can select tent type, tent color, cooling setpoint temperature (the maximal allowed indoor temperature), heating setpoint temperature (the minimal allowed indoor temperature), the number of people in the tent during days, their activity level during days, the number of people in the tent during nights, their activity level during nights, internal heat gains from equipment during days, and internal heat gains from equipment during nights. The available options for each filter are listed in Table 24.

If the user selects only one option in each filter, results for one scenario are displayed. The user can also select more options per filter. Then results for more scenarios are displayed and the user can compare different cases.



STEP 2: FILTER THE RESULTS

Type tent	Kleur	Setpoint koeling [C]	Setpoint verwarming [C]	Aantal personen - dag [-]	Activiteit - dag	Aantal personen - nacht [-]	Activiteit - nacht	Interne warmtelasten apparatuur - dag [W]	Interne warmtelasten apparatuur - nacht [W]

Figure 63 Filters

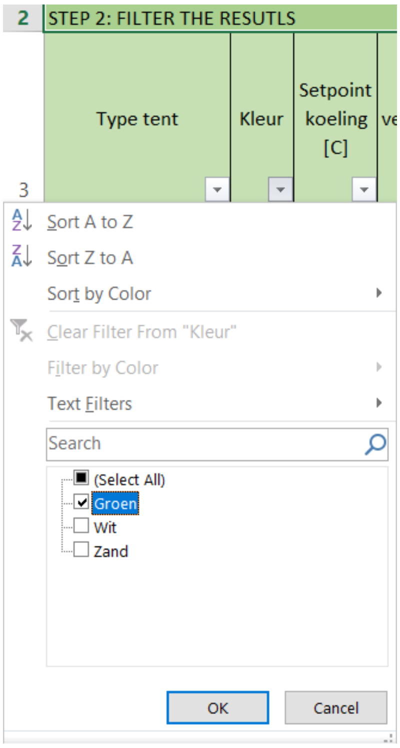


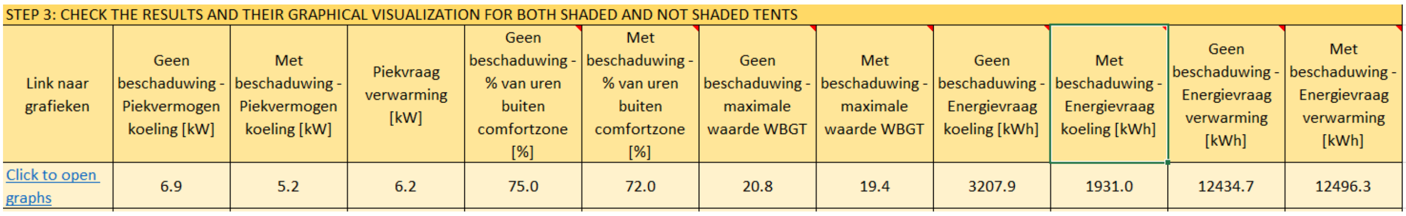
Figure 64 Results filtering

Table 24 Filtering options

Filter	Selection options
Type tent	• AD Boog • Operating tent • Multi-Purpose tent • F16 Hangar • Command post • Zumro shelter model 600 • Zumro shelter model 400 • Zumro shelter model 284
Kleur	• Groen • Wit • Zand
Setpoint koeling	• 20°C • 26°C
Setpoint verwarming	• 16°C • 20°C
Aantal personen - dag	• 0 • 10 • 30 • 100 • 300
Activiteit - dag	• Lage activiteit • Gemiddelde activiteit
Aantal personen - nacht	• 0 • 10 • 30 • 100 • 300
Activiteit - nacht	• Lage activiteit • Gemiddelde activiteit
Interne warmtelasten apparatuur – dag	• 0 W • 1000 W • 5000 W • 10000W
Interne warmtelasten apparatuur - nacht	• 0 W • 1000 W • 5000 W • 10000W

LOOK-UP TABLE OUTPUTS

After filtering the user can check the results. The results are listed in the yellow part of the look-up table as shown in Figure 65.



STEP 3: CHECK THE RESULTS AND THEIR GRAPHICAL VISUALIZATION FOR BOTH SHADED AND NOT SHADED TENTS

Link naar grafieken	Geen beschaduwing - Piekvermogen koeling [kW]	Met beschaduwing - Piekvermogen koeling [kW]	Piekvraag verwarming [kW]	Geen beschaduwing - % van uren buiten comfortzone [%]	Met beschaduwing - % van uren buiten comfortzone [%]	Geen beschaduwing - maximale waarde WBGT	Met beschaduwing - maximale waarde WBGT	Geen beschaduwing - Energievraag koeling [kWh]	Met beschaduwing - Energievraag koeling [kWh]	Geen beschaduwing - Energievraag verwarming [kWh]	Met beschaduwing - Energievraag verwarming [kWh]
Click to open graphs	6.9	5.2	6.2	75.0	72.0	20.8	19.4	3207.9	1931.0	12434.7	12496.3

Figure 65 Look-up table outputs

STEP 3: CHECK THE RESULTS AND THEIR GRAPHICAL VISUALIZATION FOR BOTH SHADED AND NOT SHADED TENTS

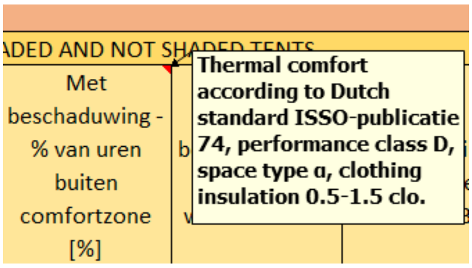
Numeric outputs

The numeric outputs can be read directly from the look-up table. The results are given for both shaded and non-shaded tents so that the user can compare them and evaluate the advantage of shading installation in the considered conditions. The results are listed and explained in Table 25.

Table 25 Numeric outputs explanation

Result	Explanation
Geen beschaduwing/Met beschaduwing - Piekvermogen koeling [kW] *English: No shading/shading peak cooling load [kW]*	The numbers represent the yearly maximum cooling load (the capacity [kW] of an air-conditioner that is required to maintain the desired cooling setpoint temperature at the most critical moment – "the hottest" moment during the year). The maximum cooling load usually occurs during a day because a lot of heat gains come from solar radiation. Due to this, shading installation decreases the peak cooling load by reduction of the solar heat gains.
Piekvraag verwarming [kW] *English: Peak heating load [kW]*	The number represents the yearly maximum heating load (the capacity [kW] of a heater that is required to maintain the desired heating setpoint temperature at the most critical moment – "the coldest" moment during the year). The maximum heating load usually occurs during the night because there is no solar radiation. Due to this, shading installation has no impact on the peak heating load.
Geen beschaduwing/Met beschaduwing - % van uren buiten comfortzone [%] *English: No shading/shading percentage of uncomfortable hours [%]*	The numbers represent the percentage of year when the indoor conditions are not comfortable according to the Dutch standard ISSO-publicatie 74 despite the installation of the HVAC system. The discomfort usually is caused by low or high radiant temperature caused by a cold or hot envelope of the tent. The comfort can be

	improved by better insulation of the tent or by adjustment of the heating and cooling temperature setpoints. It must be noted that the standard ISSO-publicatie 74 was developed for office buildings. There is no thermal comfort model developed for tents. Therefore, the thermal comfort requirements stated by the ISSO-74 standard may be too strict for military tents. The user can open a comment included in the look-up table to see the reference to the standard as can be seen in Figure 66.
Geen beschaduwing/Met beschaduwing - maximale waarde WBGT *English: No shading/shading maximal WBGT index*	The numbers represent the value of the heat stress index (WBGT) calculated based on standard ISO 7243. The index indicates if there is a risk of heat stress in the tent. The lower the WBGT index the better. The maximal allowed values of the index are listed in the table which can be found in the comment as can be seen in Figure 67.
Geen beschaduwing/Met beschaduwing - Energievraag koeling [kWh] *English: No shading/shading annual cooling demand [kWh]*	The numbers represent annual cooling energy demand [kWh] for shaded and non-shaded tents.
Geen beschaduwing/Met beschaduwing - Energievraag verwarming [kWh] *English: No shading/shading annual heating demand [kWh]*	The numbers represent annual heating energy demand [kWh] for shaded and non-shaded tents.

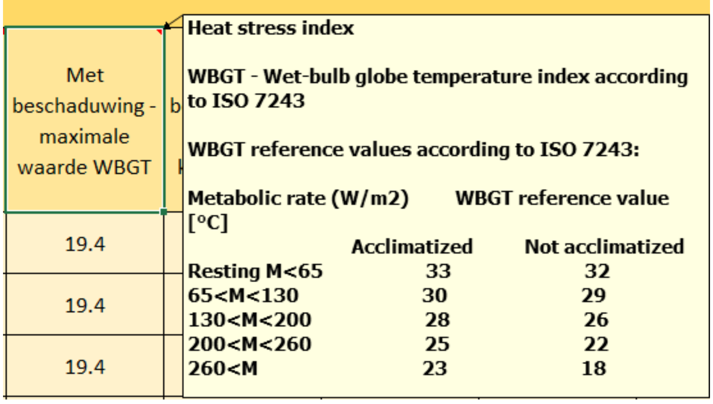


ADED AND NOT SH

Met beschaduwing - % van uren buiten comfortzone [%]

Thermal comfort according to Dutch standard ISSO-publicatie 74, performance class D, space type α, clothing insulation 0.5-1.5 clo.

Figure 66 Reference to the source of thermal comfort model



Met beschaduwing - maximale waarde WBGT

19.4

19.4

19.4

Heat stress index

WBGT - Wet-bulb globe temperature index according to ISO 7243

WBGT reference values according to ISO 7243:

Metabolic rate (W/m2)	WBGT reference value [°C]	
	Acclimatized	Not acclimatized
Resting M<65	33	32
65<M<130	30	29
130<M<200	28	26
200<M<260	25	22
260<M	23	18

Figure 67 Reference to the source of the WBGT index and the maximal allowed values of the index depending on metabolic rate

Graphic outputs

The user can also see some graphs in order to get a deeper understanding of which air-conditioner or heater should be used in a certain situation. In order to access the graphs, the user needs to click on the hyperlink ‘Click to open graphs’ in the Excel table column called ‘Link naar grafieken’. After the user clicks on the hyperlink, a pdf file pops up. The pdf file contains 24 graphs. The graphs in the left column concern a tent without shading. The graphs in the right column concern a tent with shading. The user can compare the graphs for a shaded and non-shaded tent and can draw a conclusion if it is beneficial to install shading or not.

In this manual, the graphs for a tent with no shading will be explained. The graphs for a shaded tent should be interpreted in the same way.

Figure 68 shows the cooling load duration curve for the whole year. The vertical axis represents the cooling load (the capacity of an air-conditioner in [kW]). The horizontal axis shows the percentage of the year. Actually, the horizontal axis shows the probability of exceedance. For example, if an air-conditioner of 6.5 kW is applied, the percentage of the year (or the probability of exceedance) is equal to 0. It means that the required cooling capacity is never more than 6.5 kW and therefore if an air-conditioner of 6.5 kW is applied, the required indoor air temperature can be maintained the whole year. On the other hand, if a 2 kW air-conditioner is applied, the percentage of the year (or the probability of exceedance) is about 8%. It means that if we apply an air-conditioner o 2 kW, we can expect that 8% (29.2 days in total) of the year, the required indoor air temperature is not maintained.

The cooling load duration curve can be used to make an informed decision on the air-conditioner size. The decision-maker can decide how high risk of under-sizing is acceptable and based on this select the appropriate capacity. For example, if a tent is going to serve as a hospital, probably there should be no risk of overheating. In this case, the 6.5 kW air-conditioner should be selected. If the tent is a relaxation room, probably a 4 kW air-conditioner is acceptable.

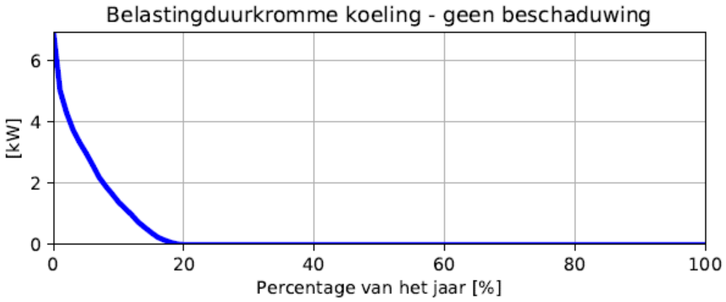


Figure 68 Cooling load duration curve for the whole year

Figure 69 shows the heating load duration curve. This curve should be interpreted similarly to the cooling load duration curve. If the user wants to be 100% sure that the heating setpoint air temperature is maintained the whole year, he should apply a 6 kW heater. If the user can accept about 4% risk, he can select a 4 kW heater.

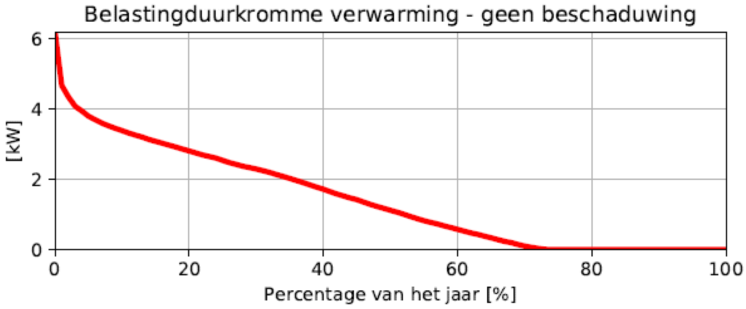


Figure 69 Heating load duration curve for the whole year

Figure 70 presents a bar chart showing the annual cooling and heating energy demand (the same as columns 'Geen beschaduwing - Energievraag koeling [kWh]' and 'Geen beschaduwing - Energievraag verwarming [kWh]' in the look-up table, respectively).

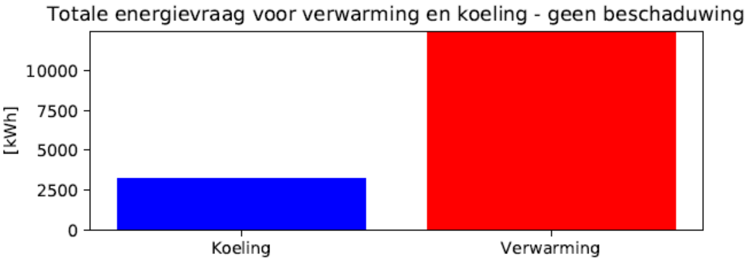


Figure 70 Annual cooling and heating energy demand

Figure 71 depicts a thermal comfort chart (according to ISSO-74). The horizontal axis represents the running mean outdoor temperature. The vertical axis represents the operative indoor temperature. Operative temperature is calculated from air temperature and mean radiant temperature. The green lines represent the thermal comfort boundaries. Each of the black dots represents one hour of the year. The dots which are in between the green lines represent "comfortable hours". The dots that are above the upper limit represent "overheating hours", and the dots below the bottom limit represent "overcooling hours". Therefore, in this case, thermal discomfort is mainly caused by low operative temperatures in the tent. The situation can be improved by increasing the heating temperature setpoint.

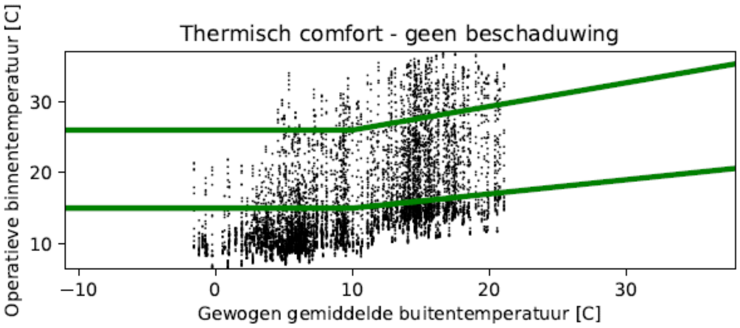


Figure 71 Thermal comfort chart (according to ISSO-74)

Figure 72 and Figure 73 show the cooling and heating load duration curves for spring, respectively. The curves should be interpreted similarly to the ones for the whole year (Figure 68 and Figure 69). The only difference is that now, 100% does not represent the whole year but just spring. For example, if a 1 kW air-conditioner is applied, during 10% of spring (about 9 days in total) the cooling setpoint temperature may be exceeded. Similar load duration curves are included in the output pdf file for the remaining seasons.

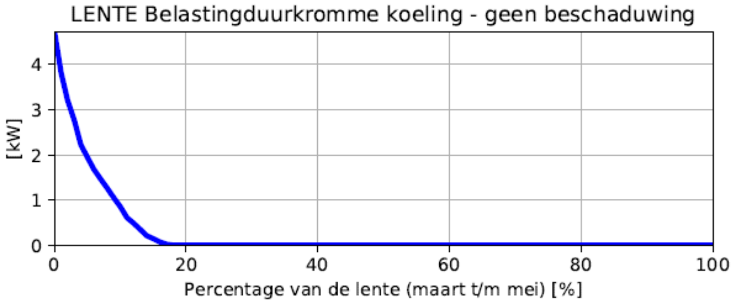


Figure 72 Cooling load duration curve for spring

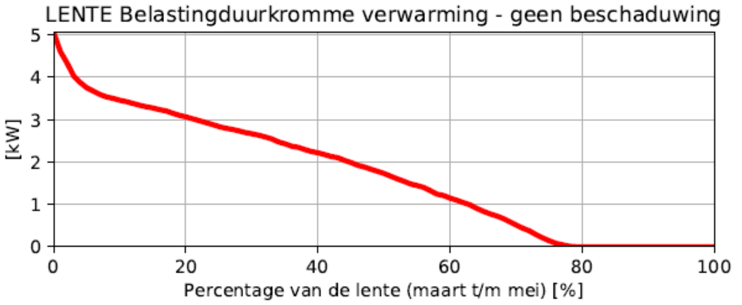


Figure 73 Heating load duration curve for spring

10.2 APPENDIX B – MODELING APPROACH USED FOR THE DST - SUMMARY

Table 26 summarizes how particular aspects were modeled. Table 27 lists the assumed values of the input parameters used in the model.

Table 26 Modeling approach - summary

Aspect	Modeling approach
Weather data	TMY
Ground temperature	Monthly average ground temperatures extracted from weather data
Tent envelope	Fully glazed
Infiltration	Constant infiltration rate
Thermal stratification	Mixed-air assumption
Plastic shading	Additional glass layer on the roof
Net shading	Shading object above the roof
HVAC system	Ideal load air system, always available, unlimited capacity, no heat recovery, no humidity control, air temperature control
Occupancy	Constant occupancy during the day, constant occupancy during the night, heat gains dependent on the activity level
Heat gains from equipment	Constant heat gains during the day, constant heat gains during the night, determined by the DST user
Thermal comfort	Adaptive thermal comfort model according to (ISSO-publicatie 74, 2014)
Heat stress risk	Assessed based on the WBGT index according to (ISO 7243, 2003)

Table 27 Assumptions used in the model

Parameter	Options	Min. value	Max. value	Unit
Fabric thermal resistance	-	0.15	0.20	[(m^2K)/W]
Fabric transmittance	Green - Opaque	0.001	0.001	[-]
	Green – Light-permeable	0.01	0.03	
	Sand - Opaque	0.001	0.001	
	Sand – Light-permeable	0.05	0.1	
	White - Opaque	0.001	0.001	
	White – Light-permeable	0.06	0.2	
Fabric absorptance	Green - Opaque	0.8	0.9	[-]
	Green – Light-permeable	0.8	0.9	
	Sand - Opaque	0.2	0.3	
	Sand – Light-permeable	0.2	0.3	
	White - Opaque	0.1	0.15	
	White – Light-permeable	0.04	0.05	

Fabric reflectance	Green - Opaque	0.099	0.199	[-]
	Green – Light-permeable	0.07	0.19	
	Sand - Opaque	0.699	0.799	
	Sand – Light-permeable	0.6	0.75	
	White - Opaque	0.849	0.899	
	White – Light-permeable	0.75	0.9	
Infiltration	Not intensive	1.5	2.5	ACH
	Intensive	3.5	4.5	
Shading net transmittance	Black	0.3	0.5	[-]
	White	0.4	0.65	
Plastic shading transmittance	Green - Opaque	0.001	0.001	[-]
	Green – Light-permeable	0.01	0.03	
	Sand - Opaque	0.001	0.001	
	Sand – Light-permeable	0.05	0.1	
	White - Opaque	0.001	0.001	
	White – Light-permeable	0.06	0.2	
Plastic shading absorptance	Green - Opaque	0.8	0.9	[-]
	Green – Light-permeable	0.8	0.9	
	Sand - Opaque	0.2	0.3	
	Sand – Light-permeable	0.2	0.3	
	White - Opaque	0.1	0.15	
	White – Light-permeable	0.04	0.05	
Plastic shading reflectance	Green - Opaque	0.099	0.199	[-]
	Green – Light-permeable	0.07	0.19	
	Sand - Opaque	0.699	0.799	
	Sand – Light-permeable	0.6	0.75	
	White - Opaque	0.849	0.899	
	White – Light-permeable	0.75	0.9	
Heat gains from occupants	Low activity level	113		[W/person]
	Medium activity level	174		
	High activity level	293		
Heat gains from occupant – latent fraction	Low activity level	0.3		[-]
	Medium activity level	0.5		
	High activity level	0.6		

10.3 APPENDIX C - MCA OF GROUND MODELING METHODS – SENSITIVITY ANALYSIS

An important part of the multi-criteria analysis is sensitivity analysis. The sensitivity analysis allows making sure that the final ranking might not be impacted by the uncertainty of data, small changes in weighting factors, or different interests of different actors. It checks the solidness of the conclusion of the MCA (Kirkels, 2018). As it was already mentioned in section 5.2.4, the sensitivity analysis can include the following actions:

1) Taking into account a range for a certain data point instead of a single value to account for uncertainty in data.
2) Using a different set of weighting factors (for example appropriate for different actors).
3) Finding a turning point for the established criteria.
4) Excluding a criterion.

Action 1) is not applicable in this case because most of the evaluation criteria are qualitative and therefore they are not described as a value. The only quantitative criterion is the simulation time which can be determined very accurately and therefore there is no point to apply any uncertainty range.

Action 2) is also not relevant for this assignment because the DST designer and developer is the only actor involved in the decision-making about the ground modeling method. Therefore, the weighting factors were established based on the subjective opinion built on previous experiences, knowledge, and interviews with the client.

Actions 3) is to find turning points for the established criteria. The turning point for a criterion is the change in the value of its weighing factor (smallest change) that causes a change in the final ranking of the alternatives. Especially a change in the first ranked option is relevant (Kirkels, 2018). The turning points help to understand how sensitive the ranking is to changes in a particular weighting factor.

Table 28 shows the turning point for the criteria. The turning points were calculated as the smallest change in a weighting factor that changes the first ranked alternative. The table proves that the ranking is very stable. The weighting factors must change significantly to influence the first ranked alternative. Another observation is that the simulation time alone has no impact on which alternative is the first one. On the other hand, the most sensitive factor is abstraction error.

Table 28 Turning points

Criteria	Original WF	Turning point WF
Robustness	25	-41
Simulation time	10	NO
Abstraction error	15	+11

Numerical error	25	-41
Input uncertainty	25	-14

Action 4) is to exclude a criterion. That was done considering various scenarios that are described below:

Scenario 1 – Baseline scenario – all five criteria are included.

Scenario 2 – The DST user agrees that the DST can stop working for some particular locations to increase the accuracy of the results for other locations. The criterion ‘Robustness’ is excluded.

Scenario 3 – The DST user agrees to wait longer for the results to increase their accuracy. The criterion ‘Simulation time’ is excluded.

Scenario 4 - The DST user agrees that the DST can stop working for some particular locations and accepts longer waiting time to increase the accuracy of the results. The criteria ‘Robustness’ and ‘Simulation time’ are excluded.

Table 29 presents the alternatives ranking for the scenarios. The top 3 alternatives are the same for all scenarios. The only changing positions are fourth and fifth. Therefore, it is concluded that the ranking is stable.

Table 29 Alternatives ranking for different scenarios

	No information about the ground in the tent model	Simple method	GroundDomain:Slab	Slab Preprocessor	Kiva tool
Scenario 1	2	1	3	5	4
Scenario 2	2	1	3	4	5
Scenario 3	2	1	3	5	4
Scenario 4	2	1	3	4	5

10.4 APPENDIX D – DECISION-SUPPORT TOOL – MANUAL

Tool for decision-making on HVAC systems' capacity for military tents

USER MANUAL

Introduction

The tool is for helping its user to make an informed decision on HVAC systems' capacity for military tents. It is user-friendly and does not require expert knowledge about HVAC systems. The tool user gets customized advice, therefore his decisions are informed, and risk, costs, and energy consumption are reduced. The tool input form is built up in MS Excel and therefore it can be used on any machine having MS Excel installed. The tool is portable, can be stored in any location (local, network or removable drive) and can run out of the box. The user needs to fill in the input form in MS Excel, click on the "Calculate" button, and the results are displayed. The tool usage algorithm is presented in Figure 74. This user manual presents an overview of the tool features and explains steps for making the informed decision on HVAC systems' capacity for military tents. Section "User input form" of this manual explains how to fill in the user input form. Explanations of the tool outputs can be found in section "Output reports".

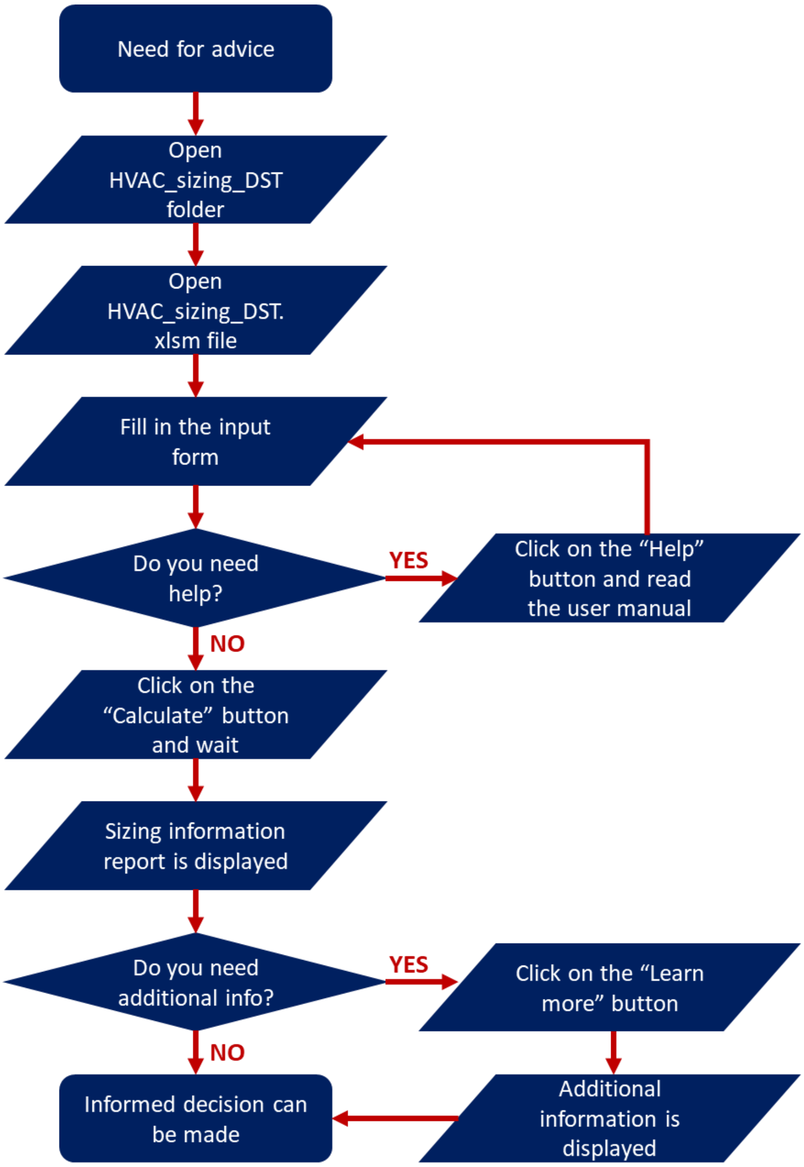


Figure 74 Tool usage algorithm

User input form

After opening the 'HVAC_sizing_DST.xlsm' file, the user must activate Macros.

All inputs in the green field (and designated with a star *) are mandatory. It means that all of them must be filled in by the user. Otherwise, the tool will not provide any results. The mandatory inputs are listed and explained in Table 30.

Table 30 Mandatory user inputs

Category	Input	Options	Comment
Location	Country	228 countries are available	The user selects one country from the list.
	City	228 cities are available (one per country)	The user selects one city from the list. The list consists of cities located in the selected country.
Tent construction	Tent shape	- Gable roof tent - Arc tent	The user selects the tent shape. An example drawing of a gable roof tent and an arc tent is given in the input form.
	Tent dimensions	To be typed by the user	The user specifies the tent's width, length, total height, and wall height. The dimensions must be given in meters. A dot (.) should be used as decimal separator.
	Tent envelope type	- Single-skin - Double-skin	The user selects the tent's walls and roof construction. - Single-skin - one layer of fabric - Double-skin - two layers of fabric with an air-cavity in between.
	Floor-type	- No floor - PVC foil - Concrete slab - Timber floor - Insulated floor plates	The user selects an appropriate floor type. If none of the available floor types is appropriate, a user-defined floor U-value can be specified in the "User-defined" section (grey box).
	Tent color	- Green - Sand - White	The user selects a tent color. Three default colors are available. If none of them is appropriate, the user can specify the fabric transmittance, absorptance, and reflectance in the "User-defined" section (grey box). The values can be provided by the tent manufacturer.
	Fabric light-permeability	- Opaque - Light-permeable	If the fabric does not permit any sunlight, the user should select "Opaque". Otherwise, "Light-permeable".
	Expected infiltration rate	- Not intensive - Intensive	The user specifies the expected infiltration intensity. "Intensive" should be selected if: - Windows and doors are expected to be open

			- The tent is made of "breathable" fabric - The area is windy - There are no obstructions that can block the wind "Not intensive" should be selected if: - Windows and doors are expected to be closed - The tent is made of plastic fabric - The area is not windy - There are obstructions blocking the wind (for example other tents)
Shading	Shading application	- No shading - Net shading - Plastic fabric shading	The user specifies a shading application.
	Shading net color	- White - Black	If a shading net is applied, the user selects the net color. Two default colors are available. If none of them is appropriate, the user can specify the net transmittance in the “User-defined” section (grey box). The values can be provided by the net manufacturer.
	Plastic fabric shading color	- Green - Sand - White	If a plastic shading is applied, the user selects the fabric color. Three default colors are available. If none of them is appropriate, the user can specify the fabric transmittance, absorptance, and reflectance in the “User-defined” section (grey box). The values can be provided by the fabric manufacturer.
	Plastic fabric shading light-permeability	- Opaque - Light-permeable	If the plastic shading fabric does not permit any sunlight, the user should select "Opaque". Otherwise, "Light-permeable".
Tent usage	Cooling temperature setpoint	To be typed by the user	The user specifies the desired indoor temperature during the cooling season.
	Heating temperature setpoint	To be typed by the user	The user specifies the desired indoor temperature during the heating season.
	Number of occupants DAY	To be typed by the user	The user specifies the expected number of occupants during the day.

	Activity of occupants DAY	- Low - Medium - High	The user selects an activity level of the occupants during the day. "Low" - sitting, resting, lying "Medium" - light work "High" - heavy physical work
	Number of occupants NIGHT	To be typed by the user	The user specifies the expected number of occupants during the night.
	Activity of occupants NIGHT	- Low - Medium - High	The user selects an activity level of the occupants during the night. "Low" - sitting, resting, lying "Medium" - light work "High" - heavy physical work
	Internal heat gains DAY	To be typed by the user	The user specifies internal heat gains from equipment during the day. More guidelines are provided below this table.
	Internal heat gains NIGHT	To be typed by the user	The user specifies internal heat gains from equipment during the night. More guidelines are provided below this table.

Internal heat gains from lighting (Q_l) can be calculated using the following simplified formula (according to ASHRAE Fundamentals Handbook):

$$Q_l = W \cdot F_{sa}$$

Where:
W – total light wattage [W]
F_{sa} - lighting special allowance factor.

For fluorescent or high-intensity discharge luminaires, the special allowance factor accounts mainly for ballast losses. For the sake of simplicity, the following lighting special allowance factors can be used (Table 31):

Table 31 Lighting special allowance factors (Based on ASHRAE Fundamentals Handbook)

Lamp type	**Ballast type**	**F_{sa} - lighting special allowance factor**
Fluorescent	Mag-Std	1.3
	Electronic	1.0
	Mag-ES	1.2
High-Pressure Sodium	HID	1.3
Metal Halide	HID	1.3
Mercury Vapor	HID	1.3
Incandescent	No ballast	1.0

Internal heat gains from equipment can be estimated using information collected in Table 32.

Table 32 Recommended rates of heat gain from equipment (According to ASHRAE Fundamentals Handbook)

Equipment category	**Equipment type**	**Heat gains [W]**	
Medical equipment	Anesthesia system	166	
	Blanket warmer	221	
	Blood warmer	114	
	Electrosurgery	109	
	Endoscope	596	
	Vacuum suction	302	
	X-ray system	480	
	Surgical light	250	
Office equipment	Computer	55	
	Monitor	55	
	Vending machine	800	
	Laser printer	180	
	Coffee machine	200	
Kitchen equipment		**Without hood**	**With hood**
	Dishwasher	130	50
	Large freezer	540	0
	Small freezer	320	0
	Refrigerator (small) per cubic meter of interior space	690	0
	Gas oven	-	1670
	Electric oven	-	850
	Microwave	600-1400	-
	Fryer (deep fat)	-	560
Hot meal	Hot meal	15 W	

Besides the mandatory inputs, the user can also fill in the “User-defined” additional inputs which can be found in the grey box. The additional inputs are listed and explained in Table 33. The user does not have to fill in the inputs in the grey box. If the input cells are empty, the tool works anyway. However, the additional inputs should be used if the considered tent or shading are made of different materials than defaults or if the user has detailed information about the materials properties.

Table 33 Additional user inputs

Input	Comment
Fabric U-value	The default fabric U-value is 5 W/(m^2K). If this assumption is not correct, the user can specify a different value.
Floor U-value	If none of the available default floor types is appropriate, the user can specify a floor U-value.
Fabric transmittance Fabric absorptance Fabric reflectance	If none of the default tent colors is appropriate or accurate transmittance, absorptance and reflectance values are known, the user can specify them. The values are in the range between 0 and 1, and their sum is equal to 1.
Shading net transmittance	If none of the default shading net colors is appropriate or if accurate transmittance value is known, the user can specify it. The transmittance value is in the range between 0 and 1.
Plastic fabric shading transmittance Plastic fabric shading absorptance Plastic fabric shading reflectance	If none of the default plastic fabric shading colors is appropriate or accurate transmittance, absorptance and reflectance values are known, the user can specify them. The values are in the range between 0 and 1, and their sum is equal to 1.

After filling in the input-form, the user should click on the “Calculate” button and wait. After some time (about 30s, depending on the computing power of the computer), the sizing information report is displayed. If the user needs more information regarding energy demand, thermal comfort or heat stress risk, he can click on the “Learn more” button to display the additional information report. When the user clicks on the “Help” button, this user manual is displayed. After clicking on the “How to understand load duration curves?” button, an instruction movie will be displayed. The movie explains how to read load duration curves, what knowledge can be gained from the curves, why they are useful, and how they help to make an informed decision on HVAC systems’ capacity instead of deciding for the user.

Output reports

After the calculations are performed, the sizing information report is displayed to the user in the PDF format. If the user needs more information, he can click on the “Learn more” button to display the report with additional information. Subsections “Sizing information” and “Additional information” discuss the sizing information report and the additional information report, respectively.

SIZING INFORMATION

The sizing information report is generated by the tool and displayed to the user. It is also saved in “OutputFiles” folder and named “Report_[year]-[month]-[day]_[hour]-[minutes]-[seconds].pdf” so that the user can open the report once again without the necessity for performing calculations once again. The information included in the report is enough for the user to support his decision on the HVAC system capacity. The report is composed of five sections: “User input”, “Detailed user input”, “Peak cooling and heating load range”, “Load duration curves for the whole year” and “Load duration curves for seasons”.

USER INPUT

The “User input” section contains all mandatory user inputs (designated with the star (*) and located on the green area of the input form). This section allows the user to make sure that the input information is correct. Moreover, it allows the user to identify the report in the “OutputFiles” folder.

DETAILED USER INPUT

The “Detailed user input” section contains all additional user inputs (located on the grey area of the input form). This section allows the user to make sure that the input information is correct. Moreover, it allows the user to identify the report in the “OutputFiles” folder.

PEAK COOLING LOAD RANGE

The numbers represent the yearly maximum cooling load (the capacity [kW] of an air-conditioner that is required to maintain the desired cooling setpoint temperature at the most critical moment – “the hottest” moment during the year). The peak cooling load is given as a range. The difference between the lower and the upper range limits is caused by uncertainties related to materials’ properties and infiltration rates.

It must be noted that the peak cooling load represents the required cooling energy flow and does not account for air-conditioning unit performance degradation or any cooling energy losses occurring for example in the air-distribution system. The air-conditioning unit performance is decreased if the unit is directly exposed to solar radiation. Therefore, it is recommended to place the unit and the air-ducts in a shade. It is also recommended to use as short ducts as possible to minimize the cooling energy loss.

The calculation procedure assumes that the air-conditioned air is fully recirculated. In order to cool down the air most efficiently, the air entering the air-conditioner should be as cold as possible. This is achieved when the air-conditioned air is recirculated. For the sizing purpose, the hottest moments during the year are relevant. It is assumed that during these moments effort is made to decrease the indoor temperature and the HVAC system is set in the most efficient recirculation mode. This assumption allows for avoiding the HVAC system oversizing during the rest of the year.

PEAK HEATING LOAD RANGE

The numbers represent the yearly maximum heating load (the capacity [kW] of a heater that is required to maintain the desired heating setpoint temperature at the most critical moment – “the coldest” moment during the year). The peak heating load is given as a range. The difference between the lower and the upper range limits is caused by uncertainties related to materials’ properties and infiltration rates.

Similarly as for the cooling load, the peak heating load represents the required heating energy flow and does not account for heating unit performance degradation or any heat losses occurring for example in the air-distribution system.

The heating loads calculation procedure assumes that the air is fully recirculated for the same reason as in the case of the cooling load calculations.

LOAD DURATION CURVES FOR THE WHOLE YEAR

The left graph in Figure 75 shows the cooling load duration curves for the whole year. The difference between the lower and the upper curves is caused by uncertainties related to materials’ properties and infiltration rates. The vertical axis represents the cooling load (the capacity of an air-conditioner in [kW]). The horizontal axis shows the percentage of the year. Actually, the horizontal axis shows the probability of exceedance. For example, if an air-conditioner of 11 kW is applied, the percentage of the year (or the probability of exceedance) is equal to 0. It means that the required cooling capacity is never more than 11 kW and therefore if an air-conditioner of 11 kW is applied, the required indoor air temperature can be maintained the whole year. On the other hand, if a 4 kW air-conditioner is applied, the percentage of the year (or the probability of exceedance) is about 20%. It means that if we apply an air-conditioner of 4 kW, we can expect that 20% (73 days in total) of the year, the required indoor air temperature is not maintained.

The cooling load duration curve can be used to make an informed decision on the air-conditioner size. The decision-maker can decide how high risk of under-sizing is acceptable and based on this select the appropriate capacity. For example, if a tent is going to serve as a hospital, probably there should be no risk of overheating. In this case, the 11 kW air-conditioner should be selected. If the tent is a relaxation room, probably a smaller capacity air-conditioner is acceptable.

The right graph in Figure 75 shows the heating load duration curve. This curve should be interpreted similarly to the cooling load duration curve. If the user wants to be 100% sure that the heating setpoint air temperature is maintained the whole year, he should apply an 8 kW heater. If the user can accept for example 1% risk, he can select a 5 – 6.5 kW heater.

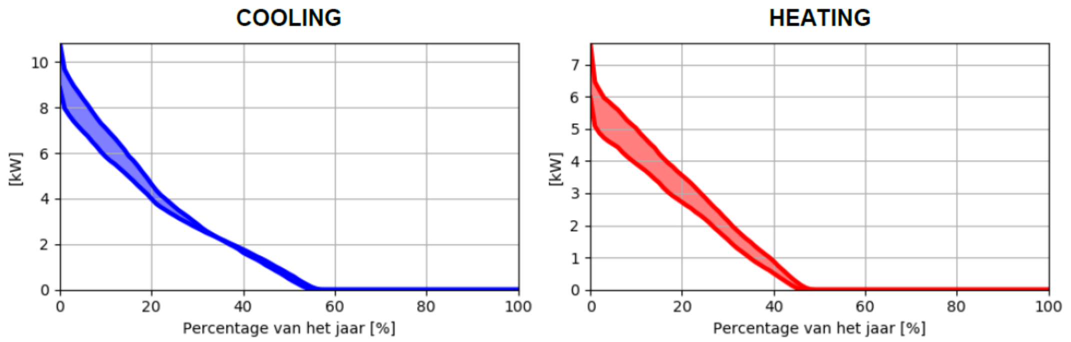


Figure 75 Cooling and heating load duration curves for the whole year – example

LOAD DURATION CURVES FOR SEASONS

Figure 76 shows the cooling and heating load duration curves for spring. The curves should be interpreted similarly to the ones for the whole year (Figure 75). The only difference is that now, 100% does not represent the whole year but just the spring. For example, if a 5 kW air-conditioner is applied, during 10% of spring (about 9 days in total) the cooling setpoint temperature may be exceeded. Similar load duration curves are included in the sizing information report file for the remaining seasons.

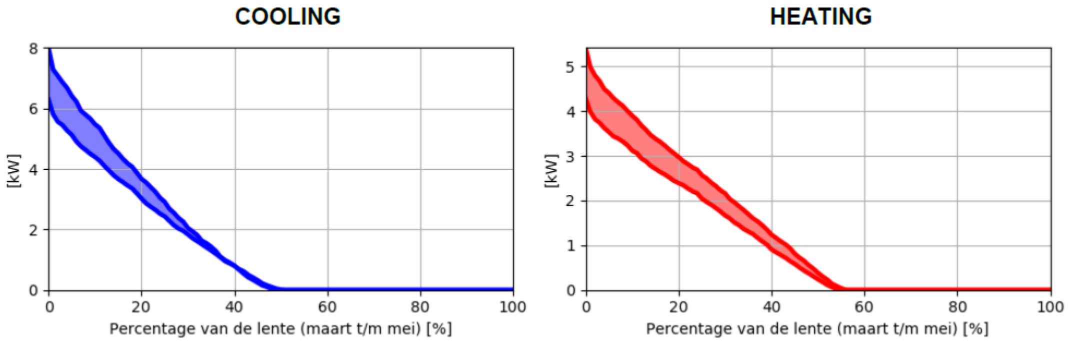


Figure 76 Cooling and heating load duration curves for seasons – spring example

ADDITIONAL INFORMATION

The additional information report can be generated on request of the user. It is displayed and saved in “OutputFiles” folder and named “AdditionalReport_[year]-[month]-[day]_[hour]-[minutes]-[seconds].pdf” so that the user can open the report once again without the necessity for performing calculations once again. The information included in the additional report concerns yearly heating and cooling energy demand, thermal comfort and heat stress danger. The report is composed of the following sections: “User input”, “Detailed user input”, “Annual cooling and heating demand”, “Percent of uncomfortable hours during the year”, “Thermal comfort” and “Maximal annual WBGT index”.

The sections **USER INPUT** and **DETAILED USER INPUT** are the same as in the sizing information report.

ANNUAL COOLING AND HEATING DEMAND

The numbers represent annual cooling and heating energy demand [kWh]. The difference between the lower and the upper range limits is caused by uncertainties related to materials' properties and infiltration rates.

It must be noted that the numbers are valid only if the assumptions related to the tent usage, occupancy, internal heat gains, HVAC system operation, and weather conditions are realistic for the whole year. Moreover, the annual cooling and heating energy demand are calculated with the assumption that the HVAC system keeps the required temperature all the time. Furthermore, it must be noted that the numbers reflect the thermal energy required to keep the indoor temperature on the desired level. Therefore, it does not directly reflect the fuel or electricity demand which is affected by the system efficiency, distribution losses, and fans' energy consumption.

The annual cooling and heating demand together with the uncertainty ranges are also visualized on a bar chart which can be seen in Figure 77.

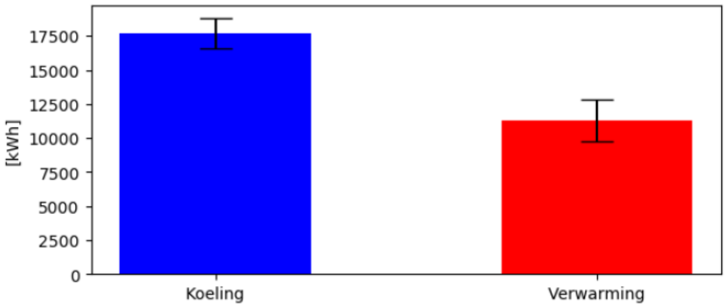


Figure 77 Annual cooling and heating demand chart – example

- **PERCENT OF UNCOMFORTABLE HOURS DURING THE YEAR**

  The numbers represent the percentage of year when the indoor conditions are not comfortable according to the Dutch standard ISSO-publicatie 74 despite the HVAC system operation. The discomfort usually is caused by a low or high radiant temperature caused by a cold or hot envelope of the tent. The ISSO-publicatie 74 thermal comfort model was not developed to be used for military tents. Therefore, the results should not be treated literally but just as a helpful indication.

  Similarly to other parameters, the difference between the lower and the upper range limits is caused by uncertainties related to materials' properties and infiltration rates.

THERMAL COMFORT

Figure 78 depicts the thermal comfort chart (according to ISSO-74). The horizontal axis represents the running mean outdoor temperature. The vertical axis represents the operative indoor temperature. The operative temperature is calculated from air temperature and mean radiant temperature. The black lines represent the thermal comfort boundaries. The green and the red dots represent the best and the worst scenarios considering uncertainties related to materials' properties and infiltration rates, respectively. Each of the dots represents one hour of the year. The dots which are in between the green lines represent "comfortable hours". The dots that are above the upper limit represent "overheating hours", and the dots below the bottom limit represent "overcooling hours".

From this chart, the user can learn what the source of thermal discomfort is and can undertake appropriate measures to improve the situation. Also, the user may prove the tent occupants that their discomfort is not caused by too low capacity HVAC system but by the weather conditions and their large impact on the tent thermal performance.

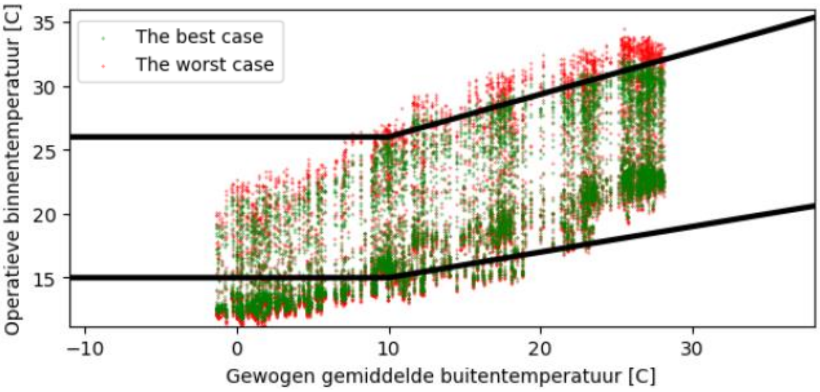


Figure 78 Thermal comfort chart – example

MAXIMAL ANNUAL WBGT INDEX

The numbers represent the value of the heat stress index (WBGT) calculated based on standard ISO 7243. The index indicates if there is a risk of heat stress in the tent. The lower the WBGT index the better. The maximal allowed values of the index are listed in Table 21.

Table 34 WBGT reference values according to ISO 7243

Metabolic rate [W/m2]	WBGT reference value	
	Acclimatized people (°C)	Not acclimatized people(°C)
Resting M < 65	33	32
65 < M < 130	30	29
130 < M < 200	28	26
200 < M < 260	25	22
M > 260	23	18

10.5 APPENDIX E - RECOMMENDATIONS FOR THE MOBILE HEATERS AND AIR-CONDITIONERS USE

To achieve the highest performance and reliability from the HVAC system and to decrease power consumption, the system should be carefully installed.

- The bending of air ducts should be avoided because it increases pressure losses. It may result in a decrease in the airflow rate and the cooling or heating capacity.
- The air ducts should be as short as possible to minimize pressure and thermal energy losses.
- The air ducts should not be blocked because it decreases the airflow rate and therefore also the capacity.
- To achieve the best performance, limit the infiltration and natural ventilation in the tent by closing doors and windows. However, make sure that acceptable air quality is maintained in the tent.
- To achieve the highest efficiency, the air should be fully recirculated. Therefore, when peak demand occurs or if there is a need to cool down or heat the tent quickly, the recirculation setting should be used. However, if the tent is occupied, enough ventilation should be provided to ensure acceptable air quality.
- The air-conditioners and heaters should not be obstructed by other objects to ensure free airflow and fumes removal.
- The supply air should be distributed uniformly in the tent. For this, an air distribution plenum can be used. For cooling, the supply plenum should be installed under the roof and the return duct above the floor. On the other hand, for heating, the warm air should be supplied to the bottom part of the tent and extracted from the upper part.
- The air-conditioners should be placed in a shadow if possible.