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ASSESMENT OF THE THERMAL ENVIRONMENT IN VEHICULAR CABINS

HODNOCENÍ TEPELNÉHO PROSTŘEDÍ KABIN AUTOMOBILŮ

SHORTENED DOCTORAL THESIS

TEZE

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CONTENT

1 INTRODUCTION

1.1 CHALLENGES IN THE VEHICULAR MICROCLIMATE

People in developed countries spend substantial parts of their lives in indoor environments both during free time and while working [1]. For this reason, there has been increasing interest in the quality of the indoor environment. The main emphasis of past research has been directed towards understanding the fields of human health, productivity, and comfort. One important contributor to all three fields is the thermal aspect of the environment, which is often represented by physical quantities such as air temperature, radiant temperature, air humidity, and air velocity. While weather-independent control of these parameters is possible via heating, ventilation, and air-conditioning systems (HVAC), a major limitation is that these systems are related to substantial energy consumption and carbon footprint. In steady conditions, vehicular cabin thermal management contributes to approximately 7 % of vehicle total energy consumption, yet, a four-fold rise may occur during peak loads [2,3]. Moreover, in electric vehicles, the available energy for microclimate management comes at the cost of driving range, and therefore, new solutions for more effective and human-centred ways of managing the indoor microclimate are sought.

One of the promising ways to address these issues is local conditioning via seats or radiant panels operating in synergy with an HVAC unit [4–6]. At the same time, the optimization and research tasks are being shifted towards virtual investigation to mitigate the need for costly and often ethically concerning human studies. To do so, models of human thermo-physiology and thermal sensation/comfort have been devel-oped. Yet, for their reliable applications, factors regarding high heterogeneity, clothing, the thermal mass of the adjacent surfaces, and seat conditioning have not been resolved.

2 SPECIFICS OF THE VEHICULAR MICROCLIMATE

Vehicular cabins, as well as cabins of commercial and working vehicles, differ from built environments in many aspects summarized in the following points:

- a broad range of temperature (-20 ° to 60 °C) and air humidity (5 % to 100 %) [7], transient and asymmetric in nature;
- small air volume per person and consequent need for active ventilation and conditioning;
- solar irradiation and substantial heat exchange at skin induced by higher local air velocities and contact with adjacent surfaces (e.g. seats and steering wheel);
- fixed body position; and
- priority of auxiliary HVAC functions to prevent fogging and icing of the windows.

Weather-related heat load can be amplified due to the nature of cabins (e.g. by the greenhouse effect or lack of air-conditioning) and lead to discomfort or heat stress. In private passenger transportation, the duration of a typical car trip is no longer than 20 minutes [4]. Such a short period of time is often insufficient for the HVAC unit to establish comfortable conditions. Inappropriate thermal conditions account for a negative impact on a driver's performance [5] and health [6]. Thus, a state of thermal comfort is not only important for the pleasant thermal experience but also for prevention of driver's fatigue and related hazards in traffic.

Although technologies for personalized conditioning are available, their control is solely based on user interaction. The user reaction is delayed to a point when discomfort arises and is accompanied by negative effects such as rebound or overshoot [5]. Additionally, manual adjustments of the conditioning cause distraction and might have medical consequences when used improperly, such as low-temperature skin burns (*Erythema ab igne*) [8]. In the case of prolonged use of air-conditioning, mucous membrane irritation, fatigue, and headache are well-known symptoms. Although, their source is not clearly defined, it is usually ascribed to a combination of factors such as poor hygiene of the HVAC systems [9] and excessive cooling by a stream of cold, dry air.

The same regulatory principles can be found in up-to-date HVAC systems with manual control. An automatic control regime takes into consideration one user input, temperature, and external system inputs such as exterior and interior temperatures, air humidity, solar intensity, to treat and distribute the air in the cabin [10]. Nevertheless, this approach is based on proprietary empirical tuning of the HVAC system rather than on a well-founded method.

2.1 HUMAN PHYSIOLOGY WITH REGARDS TO THERMAL SENSATION AND COMFORT

2.1.1 Human thermoregulation

To sustain the vital functions of a human body, its core temperature has to be maintained within a relatively narrow temperature range of ~36.7 ± 0.5 °C [11]. This temperature maintenance can be achieved in spite of variability of the ambient environment by equalling the heat production and heat loss as well as by transferring the heat within the body. The two main thermoregulatory mechanisms are behavioural and autonomic. Behavioural thermoregulation relates to conscious changes in body position and clothing that influence the heat balance. Autonomic thermoregulation comprises physiological responses, such as vasomotion, shivering, and sweating, which help to conserve or to dissipate the body heat. From the thermoregulatory point of view, human skin is the most important element accounting for approximately 92 % of the heat exchange between the body core and the ambient environment. The rest is attributed to the respiratory heat exchange [12].

2.1.2 Perception of thermal sensation and comfort

The surrounding thermal conditions are sensed by peripheral cold- and warmth-sensitive receptors distributed within subcutaneous tissues. The second group of thermoreceptors, central receptors, are located along blood-vessels and in hypothalamus [13]. Although the density of the peripheral receptors is difficult to quantify, it could be expected to see a positive correlation between their number and sensitivity of hot and cold spots on the skin surface [14]. The distribution of such spots is not uniform over the human body and thus heating or cooling of different body parts is perceived differently [13,14].

In thermal comfort studies, the thermal sensory perception has been simplified into two respective descriptors, thermal sensation and thermal comfort. The definition of the thermal sensation can be found in standards (e.g. ISO 7730 [15], ISO 10551 [16], and Handbook Fundamentals ASHRAE [17]) as "a conscious feeling commonly graded into the categories *cold, cool, slightly cool, neutral, slightly warm, warm, hot;* it requires subjective evaluation". The neutral thermal sensation is related to the thermal balance between a human body and the ambient environment. Subtle differences in thermal perception can be also dependent on the age, sex, body composition and acclimatization [18,19]. This heat exchange is influenced by a number of factors, dominantly by metabolic activity, clothing, and the environmental parameters. When the human body is cooled at a higher rate than it is generating heat, one would perceive thermal sensation below thermo-neutrality and vice versa for thermal sensation above thermo-neutrality.

Thermal comfort, on the other hand, is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [17]. Cabanac stated that state of thermal comfort is a stable state, as opposed to the dynamic pleasure, and can last indefinitely if the environment and the subject remain in stable conditions [20]. Moreover, the complexity of predicting thermal comfort is greater than that of thermal sensation since it depends on psychological, cultural, and other personal factors. It had been generally assumed that a neutral thermal sensation was essential to achieve thermal comfort [21]. This was contradicted, however, in the study by Humphreys and Hancock [22], where the participants voted for the desired thermal sensation other than neutral in more than 40 % of cases. Nevertheless, the votes were typically in the close to thermo-neutral conditions, where only subtle thermoregulatory actions were needed such as vasomotion, rather than sweating or shivering.

While the ultimate objective of indoor environment research is to find indices to design comfortable indoor environments, this is difficult without knowing the sources of discomfort. Since the perception of discomfort is subjective and is mainly related to the thermal sensation, it is meaningful to focus on the investigation of thermal sensation. Further, it is of major interest to allow individual occupants to have control over the fine adjustments of the local microclimate. Primarily, this creates the best prerequisites to mitigate the interpersonal differences in perception of comfortable conditions. Secondly, this also induces the positive alliesthesia, which is always perceived as comfortable. Besides, it was shown that the psychological aspect of having control over the environment improved satisfaction with the indoor conditions [23,24].

2.2 FACTORS INFLUENCING THERMAL SENSATION

2.2.1 Environmental factors

Environmental factors are characterized by air temperature, mean radiant temperature, relative humidity, and mean air velocity. The environmental conditions can be determined using conventional methods. Otherwise, the desired environment can be simulated using tools with various levels of complexity, starting with analytical single-purpose models (e.g. a cabin model [25]) and ending with fine mesh CFD models [26].

With respect to the operating conditions of car cabins, environmental parameters are typically heterogeneous and change with time. In summer season, for instance, the range of comfortable conditions can be roughly characterized by air and mean radiant temperatures between 23 °C and 27 °C, relative air humidity between 30 % and 60 %, and air velocity below 0.4 $m \cdot s^{-1}$ [27]. However, thermal conditions after entering the cabin are usually different from the desired ones because of the previous cabin exposure to the weather. The HVAC is usually initiated after entering the cabin with consequent intensive cooling or heating. These situations may lead to activation of the thermoregulatory mechanisms and substantial discomfort.

2.2.2 Clothing

Clothing provides a barrier preventing heat and vapour transfer from the skin to the ambient environment or vice versa. For this reason, it is one of the most important personal factors influencing the thermal balance of a body and consequently thermal sensation. In the field of thermal comfort, clothing thermal properties are described by clothing area factor, intrinsic clothing insulation, and evaporative resistance. The clothing area factor f_{cl} represents a ratio of clothed area A_{cl} (m^2) to nude body surface area A_{sk} (m^2).

$$f_{cl} = \frac{A_{cl}}{A_{sk}} \quad (1)$$

Next, intrinsic clothing insulation I_{cl} ($m^2K·W^{-1}$) describes the actual thermal insulation from the body surface to the outer clothing surface (including enclosed air-layers). The I_{cl} can be determined according to equation 2 [28], from the f_{cl}, the adjacent air layer insulation I_a ($m^2K·W^{-1}$), and the total thermal insulation I_{tot} ($m^2K·W^{-1}$). The last two parameters are defined as a temperature gradient from the skin to the ambient environment divided by a dry heat loss measured on a naked and clothed manikin, respectively.

$$I_{cl} = I_{tot} - \frac{I_a}{f_{cl}} \quad (2)$$

The last clothing parameter, the evaporative resistance $R_{e,cl}$ ($m^2Pa·W^{-1}$), is defined in analogy to intrinsic clothing insulation (equation 3). Here the $R_{e,T}$ ($m^2Pa·W^{-1}$) denotes total evaporative resistance and $R_{e,a}$ ($m^2Pa·W^{-1}$) is vapour resistance of the boundary (surface) air layer around the outer clothing or, when nude, around the skin surface.

$$R_{e,cl} = R_{e,T} - \frac{R_{e,a}}{f_{cl}} \quad (3)$$

All three properties are highly dependent on a local air gap distribution [29,30], which is inherently shaped by a body position [31] as well as body movement [32,33]. In cabin environments, the number of possible body positions is reduced to a sitting position without body motion. However, the differences in clothing thermal properties between seated and standing body positions are known for global values (whole-body) [34–36]. Nevertheless, the availability of local clothing properties is limited since conventional sources (e.g. ISO 9920 [28]) provide only global (whole-body) values having a unit clo (1 clo = 0.155 $m^2K·W^{-1}$). Alternative methods exists and can be classified accordingly: (a) analytical heat transfer modelling [37,38]; (b) regression modelling [39]; (c) empirical modelling, e.g. the UTCI model [40]; and (d) ISO based estimation [28,41,42]. However, the precision of such methods has not been assessed and therefore may be a source of an unknown error.

2.2.3 Seat

A seat plays a significant role in the thermal experience because of its large contact area with a human body, its considerable thermal mass, and potentially extreme initial temperature. Thus, the seat may become either a heat source or a heat sink, substantially influencing the local skin temperature and thermal sensation. Additionally, seats are frequently equipped with conditioning, such as seat heating and ventilation. Nevertheless, seats are currently approached as thermal and evaporative resistance [43–46] rather than an active component interacting with skin. While this approach might be sufficient in mild and static thermal environments (e.g. offices), it is clearly unsuitable in cabin conditions.

To resolve the dynamic thermal interaction at the occupant-seat interface, one can carry out measurements using dedicated heat flux blankets (e.g. blankets by Mahoele Messtechnik, Germany). However, the experimental approach is laborious and applicable only in laboratory conditions. Alternatively, the thermal interaction with seats can be calculated using laws of physics. However, such models are either proprietary (e.g. a module in THESEUS‑FE, Germany) or the models lack conclusive and transparent validation [47–49].

The next parameter related to seated position is the occupant-seat contact area, which conditions the resulting thermal interaction. However, human subject studies on this subject are scarce and the methods usually lack details [50,51]. As an alternative, one can find contact areas determined by circumscribing a thermal manikin seated on a seat [52,53]. Nevertheless, it is reasonable to expect that the contact area of a hard-shell and lightweight manikin body is not the same as that of a human body with compressible tissues. To allow for personalised calculations of heat exchange between the seat and its occupant, it is of major interest to find a relationship between the contact area and human anthropometry.

2.2.4 Metabolic heat production

Metabolic heat production is an influential factor, and results from thermogenesis induced by exercise (muscle activity), non-exercise activity (basal metabolism), and diet-induced thermogenesis (digestion of food) [18]. In thermal sensation/comfort research, the cold-induced thermogenesis (muscle shivering or non-shivering thermogenesis) [54] is usually avoided, since it is a mechanism activated *far* from thermo-neutral conditions. The metabolic heat production is typically related to surface skin area or body mass to reduce the interpersonal variability in its estimation. A metabolic rate of a healthy, sitting person at rest is 58.2 $W \cdot m^{-2}$, which is also a definition of a unit *met* [55]. In the cabin conditions, while highway driving or resting, this is typically between 1 and 2 met [56]. Low metabolic production, on the other hand, also implies that even small changes in the environment may imbalance the thermal equilibrium.

2.2.5 Influence of body composition, age, and sex

The last group of personal factors, including body composition, age, and sex, has a relatively minor impact on the thermo-neutral zone compared to the previous factors, but it may become relevant in greatly different populations. With regards to body composition, adipose tissues act as a natural barrier against heat dissipation from the core. The shift in the thermo-neutral zone can be as high as 5 °C if two populations having 5 mm and 30 mm of the subcutaneous fat layer, respectively, are compared [18]. Next, a study by Inoue et al. [19] demonstrated a decreasing ability to sense heat or cold with increasing age as well as higher sensitivity of females to innocuous warm and cold thermal stimulation than males independent of age. The justification for this trend is given in decreasing sensitivity of elderly to thermal stimuli as well as impaired control of neural vasoconstriction, which can be also related to the lower fitness level [18,19]. Finally, the differences between sexes are usually explained by body characteristics and physiology with an upward shift of the thermo-neutral zone in women relative to men [57].

3 ASSESSMENT OF THE THERMAL ENVIRONMENTS IN VEHICULAR CABINS

The prevailing ways to examine thermal comfort are field and climatic chamber studies [58]. However, with regards to the broad scope of possible situations in cabins, fully experimental research may become unfeasible. Experimental studies require dedicated equipment and a substantial amount of time and resources. An alternative to the elaborate experimentation is mathematical modelling of human physiology, developed with the intention to substitute for physical human studies [59,60]. Such models allow virtual investigation of a physiological response of the human body to various environmental stimuli. The major advantage of simulations is their versatility and instant availability of the results. However, only a limited amount of well-documented thermo-physiological models exist having sufficient accuracy of predicted parameters [61,62]. The thermo-physiological outputs can be coupled with thermal sensation and comfort models. Thermal sensation models relate objective parameters (e.g. skin and core temperatures) with a thermal sensation or comfort vote, to rate the thermal environment on a dedicated scale [63].

3.1 MODELLING OF A HUMAN THERMAL RESPONSE

Although numerous models were proposed, their actual implementation is challenging because of the vast input parameters and working knowledge required. Additionally, a benchmark comparison of the performance of various models with respect to local predictions is scarce [60]. For this reason, the selection of a model is usually driven by its intended application, its availability, and range of available validation. Based on these criteria, the moels can be divided into categories denoting the number of human tissue layers (nodes) and the number of body parts (segments). For automotive applications, it is reasonable to use multi-node and multi-segments models with a resolution of at least anterior and posterior aspects of the limbs, torso, and head. This is crucial for the investigation of local as well as transient thermal responses and consequent modelling of local thermal sensation.

An example of a well-documented, validated, and commonly used model is the Fiala physiological and comfort model (FPCm 5.3, Ergonsim, Germany) [64]. The model allows simulation of local time-dependent human thermal responses, such as skin and core temperatures and sweat rates. The model was validated in a range of ambient temperatures from 5 °C to 50 °C and exercise levels from 0.8 met to 10 met [61,62,65,66] in both symmetric and asymmetric thermal environments and conditions with constant ambient temperature, step change temperature, and temperature ramp. It was shown that the accuracy local and mean skin temperature was typically better than a standard deviation of measurement.

3.1.1 Input parameters for thermo-physiological models

A chain is no stronger than its weakest link and this saying is also valid in modelling, where the *weakest link* is typically the quality of the input parameters, which then determine the quality of the outputs. The most commonly used input parameters in thermo-physiological modeling are environmental parameters (see Section 1.4.1), clothing thermal properties (see Section 1.4.2), and metabolic heat production (see Section 1.4.4). Alternatively, one can prescribe heat flux density or temperature, directly at the skin of a given body part. This can be used as a representation of conductive heat exchange to simulate the effects of seats and local conditioning.

Anthropology (height, weight, adipose tissue layers), age, sex, fitness level, and acclimitisation can be considered as a separate category of input parameters for thermo-physiological modelling. It is because of their impact on both passive and active components of the thermo-physiological models. As the majority of thermo-physiological models were created and validated for an average and often unisex person, efforts in thermo-physiological modelling are aimed towards a higher degree of personalisation.

3.2 THERMAL SENSATION MODELS

3.2.1 PMV-PPD model – global approach

One of the earliest and best-known models is the PMV-PPD model from ISO 7730 [15] predicting thermal sensation and a rate of discomfort based on environmental parameters (ambient temperature, mean radiant temperature, air velocity, relative air humidity), clothing (whole-body thermal insulation), and metabolic production. The range of the model's applicability covers moderate activities from 0.8 to 4.0 met, clothing in a range of 0 to 2 clo, air temperature within 10 °C and 30 °C, and air velocity below 1 $m \cdot s^{-1}$. The model is valid in stationary conditions or conditions with minor fluctuations of one or more variables [15]. However, in the cabin conditions with characteristics previously described, it is meaningful to use an approach that would recognise thermal sensation locally, at major body parts. A local thermal sensation model may help to identify the local source of discomfort that can potentially skew the resulting global thermal sensation or comfort [67]. Thus, the source of discomfort can be addressed locally, rather than attempting to change the whole microclimate around a body.

3.2.2 Local thermal sensation models

With respect to the sitting body position, spatial asymmetry, and transient environment, three well-documented thermal sensation models come into consideration to evaluate cabins. Firstly, the model by Nilsson [68] based on heat transfer (MTV), being part of the ISO 14505 [44], was developed for automotive applications with a resolution of 18 body parts. In principle, this approach assumes that a certain heat flux from the skin corresponds to a thermal vote expressed on the 7-point Bedford scale. This scale combines thermal sensation votes with thermal comfort (much too cold, too cold, cold but comfortable, neutral, hot but comfortable, too hot, much too hot). The method is applicable under a range of ambient temperatures from 19 °C to 29 °C and metabolic heat production equivalent of sedentary activities, such as driving. The main advantage of MTV is its simplicity and possibility to couple with thermal manikin measurements. On the other hand, the model lacks a derivative component, and thus, it might not perform well in rapidly changing environments.

The second model dedicated to the vehicular cabins by Zhang (TSZ) [69,70], relates local skin and core temperatures (and their time derivatives) to thermal sensation at 15 body parts. These data are typically supplied from a thermo-physiological model. The local thermal sensation is predicted on the extended 9-point ISO scale, having two additional extreme thermal sensations votes (very cold and very hot). The model was developed in a range of air temperatures between 20 °C and 33 °C and is valid for seated metabolic production. The experiments to construct the model were carried out at the University of Berkeley in California, where, the climate is rather mild, throughout the year, with hot summers. For this reason, subjects may perceive cool and cold thermal sensation differently than subjects acclimatized to cold environments, which was apparent in the study by Koelblen [71].

The third candidate, the model by Jin et al. (TSV) [72], uses local skin temperatures as inputs and yields local thermal sensation on the 7-point ISO scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot) [15]. Although the TSV model contains no derivative component, it is claimed to be suitable for transient conditions with cooling as well as for stable thermal conditions. The model was developed on the Chinese population in conditions between 20 °C and 30 °C of ambient temperature wearing summer and winter indoor clothing sets of 0.4 clo and 0.9 clo, respectively. This, again, opens questions on applicability of the model on other populations, with different cultural and climatic background.

3.2.3 Manikin-based methods

Thermal manikins are the-state-of-the-art devices applicable in various branches of clothing research and environmental engineering. The most realistic quantification of heat and mass transfer is achieved by their human-like shape as well as by mimicking body motion and sweating. However, the manikin´s purchase costs are high and they can be substituted by a less complex device dedicated to a specific application such as: (a) a body part manikin (usually head, feet, torso, or hands); (b) an omnidirectional elliptical sensor [73]; and (c) a directional surface sensor [44]. However, the shape and size of the device matters and the results from two geometrically distinct devices may not be directly comparable [74].

Thermal manikins, body sectors, and sensors can operate in various control modes:

- constant surface temperature (usually 34 °C) corresponds to average skin temperature in close to thermo-neutral states under low metabolic production [74].;

- constant heat flux control mode is technically the simplest approach that can be used to mimic certain metabolic heat production. Yet, the manikin's surface temperature can reach unrealistically high values compared to a human if insufficiently cooled; and
- comfort temperature operation mode relates the skin temperature with the metabolic heat production according to the Fanger's linear equation [44]. Asll of the three control modes are suitable only for examination of dry heat losses and, therefore, disregarding sweating.

Nilsson et al. [43,68,74] introduced the so-called clothing independent comfort zone diagram that relates equivalent temperature (t_{eq}) determined by a manikin to thermal sensation and comfort for 18 body parts. The t_{eq} is defined as a temperature of an imaginary enclosure with the air temperature equal to the mean radiant temperature and with still air. Consequently, a manikin or subject would have the same heat exchange as if placed into the actual heterogeneous environment having the same clothing. This premise is valid only for matching body positions and metabolic heat production. The equivalent temperature can be determined for the whole body or for a segment accordingly:

$$t_{eq} = t_s - \frac{Q}{h_{cal}} \quad (4)$$

where t_s (°C) is the skin surface temperature, h_{cal} (W·m^{-2}K^{-1}) is the combined heat transfer coefficient, determined under calibration conditions, and Q (W·m^{-2}) is the sensible (dry) heat loss [44]. Nilsson worked with a presumption that the equivalent temperature correlates with the mean thermal vote (MTV) and the relationship was described by a regression equation 5:

$$t_{eq,zone} = t_s - R_T(a + b \cdot MTV_{zone}) \quad (5)$$

where R_T (m^{2}K·W^{-1}) is the total thermal insulation; a and b are the regression constants [68].

With the aim of evaluating the MTV, the t_{eq} is plotted in a diagram corresponding to certain clothing set. This makes this method easy to apply. However, the price for simplicity is compensated with several methodological limitations:

- equation 5 is valid in conditions where no evaporation of sweat is present; only sensible (dry) heat loss is considered. In cabins, the risk of sweating is relatively high in warm conditions and at the less ventilated body parts such as at seats. Additionally, the sweat can already present before entering the cabin and cause higher rate of cooling;
- clothing is restricted to *indoor* (office) attire. This can be a major limitation in settings where insulating and impermeable garments are worn (rescue and military services);
- metabolic production of around 1.2 met, which suits driving or sitting light activities only. There is no consideration of other personal factors. In several occupations, intermittent driving is expected and this condition may not apply (e.g. delivery and rescue services).

3.3 VIRTUAL AND HARDWARE DEMONSTRATOR TO PREDICT THERMAL SENSATION

The focus of this section is to summarise knowledge gaps in modelling of human thermal physiology and thermal sensation as well as in their practical applications with regards to vehicular cabins. The emphasis is given to the investigation of a sitting body position and the use of local seat conditioning such as seat heating and ventilation. This summary should yield the specification of a validated modelling methodology, based on physical and physiological principles to evaluate thermal sensation. Next, similar principles should also be applicable in a physical demonstrator, which can be utilised in a thermal sensation-driven feedback control loop.

3.3.1 Concept of the methodology

The structure of the methodology to predict thermal sensation can be divided into virtual and physical approaches (Figure 1). In virtual environments, local boundary conditions describing the environment, clothing, activity, and seat must be specified. These parameters are fed to a suitable thermo-physiological model, which yields an average human response in the form of physical quantities, such as skin temperatures, rectal temperature, sweat rates, or heat fluxes at the skin. Finally, the outputs from the thermo-physiological model are translated into the predicted thermal sensation vote using a dedicated model.

The second branch (Figure 1) represents an approach applicable in real cabin conditions. Here, it is of main interest to replace costly laboratory equipment, such as thermal manikins, with cost-effective sensors installed permanently in a cabin. The set of sensors should be able to determine the local heat flux by a given surface temperature (equivalent temperature) with comparable accuracy to the thermal manikin. Depending on the application, the sensor control mode has to be selected. The measured physical quantity is again converted to a local thermal sensation vote by a thermal sensation model.

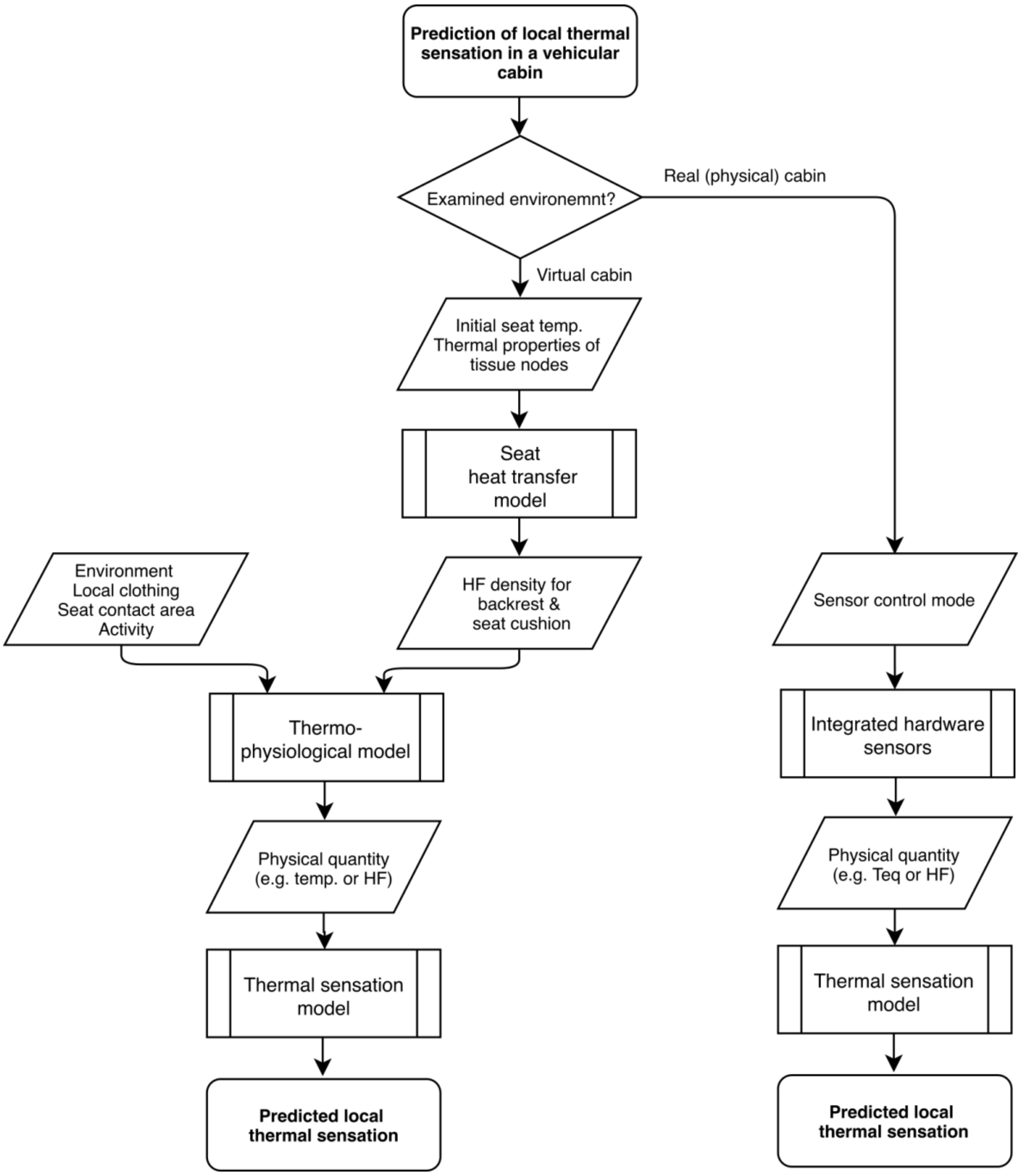


Figure 1. Structure of the methodology to predict thermal sensation in a vehicular cabin.

3.3.2 Summary of the knowledge gaps to be addressed in the thesis

Although the knowledge and technological advancements in the field of thermal comfort are extensive, their applicability in the cabin environment is still limited. The contemporary status and interaction of the three main components of the methodology is presented in Figure 2. Further, the most influential knowledge gaps on further development of the methodology are as follows:

- local clothing thermal properties, clothing area factor (f_{cl}), intrinsic clothing insulation (I_{cl}), and evaporative resistance ($R_{e,cl}$) for the sitting body position are unavailable in the literature and there is dependence on own manikin measurements;
- there is no realistic representation of a seat contact area in current thermo-physiological models and the contact area dependence on the body morphology is unknown;

» unavailable methodology for realistic representation of a seat conditioning and thermal diffusivity of a seat and its impact on human thermal response and thermal sensation in transient conditions; and

» a lack of a cost-effective hardware system capable of coupling with a suitable thermal sensation model for thermal sensation-driven HVAC applications.

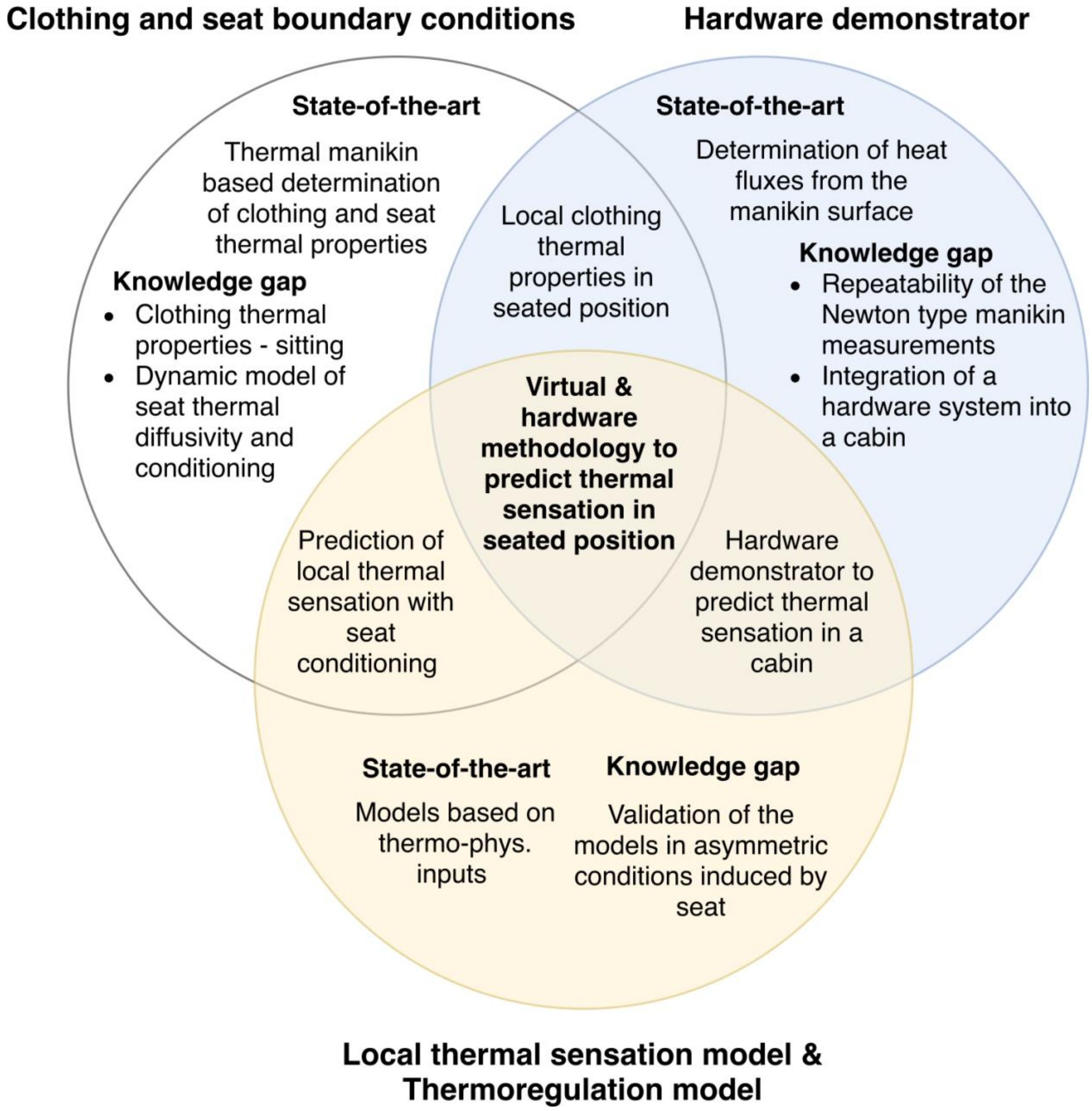


Figure 2. Summary of the state-of-the-art knowledge and knowledge gaps related to the three components of the methodology to to predict thermal sensation in a vehicular cabin.

4 AIM AND OBJECTIVES

4.1 AIM AND THESIS

The literature survey and knowledge about the specifics of predictions of thermal sensation in a vehicular cabin led to the formulation of the following thesis:

A set of tools comprising a seat heat transfer model, a realistic estimate of local clothing properties, a thermophysiological model, and a thermal sensation model can be used to evaluate thermal interactions between the human body and the surrounding environment. Further, this set of tools can be used to assess thermal sensation in the cabin environment using an objective parameter, such as equivalent temperature. These parameters can be measured in real-time and serve as advanced feedback for the thermal sensation-driven control of local conditioning technologies and HVAC.

Therefore, the aim of this thesis was to develop a methodology to assess human thermal sensation while in a sitting body position, including local conditioning factors such as heated and ventilated seats. A requirement of the method was applicability in both virtual and real indoor spaces. In the latter case, the focus was a thermal-sensation-driven feedback loop allowing for human-centred microclimate management. The particular interest is in an average thermal sensation response of a pool of adult healthy subjects, rather than individuals and/or children.

4.2 OBJECTIVES

The specific objectives of the PhD project have been formulated based on the aim of the work presented in Section 3.1 and the knowledge gaps presented in Section 2.3.2, and are as follows:

1. to develop a model relating the seat contact area to basic anthropometric measures (such as body height and weight) and to find a proper representation of the seat contact area in thermo-physiological models;
2. to assess differences between the sitting and standing body positions in the local clothing parameters (f_{cl}, I_{cl}, and $R_{e,cl}$);
3. to identify the impact of differences among typical approaches to determine local clothing parameters and to perform a sensitivity analysis of these on a simulated thermo-physiological response;
4. to develop and validate a model calculating heat transfer between a human body and a seat including local seat conditioning technologies (heating and ventilation);
5. to validate the predicted thermo-physiological responses using the local clothing and seat boundary conditions on a basis of original and literature experimental data;
6. to predict local thermal sensation using several thermal sensation models under steady, transient, and heterogenous conditions indiced by local conditioning and to identify the best performing thermal sensation model;
7. to develop a hardware demonstrator capable of exploiting the validated methodology to determine the equivalent temperature in a vehicular cabin; and
8. to implement the hardware demonstrator in a vehicular cabin and to demonstrate its functionality in a vehicular cabin against a reference, the Newton-type thermal manikin.

4.3 STRUCTURE OF THE THESIS

The aim and objectives, outlined in the previous section, have been addressed in five peer-reviewed, scientific publications. The number of citations as of July 20 2019 is given in brackets (data from Google Scholar):

I. **M. Fojtlín**, A. Psikuta, R. Toma, J. Fišer, M. Jícha, Determination of car seat contact area for personalised thermal sensation modelling, PLoS One. 13 (2018) 1–16. doi:https://doi.org/10.1371/journal.pone.0208599. (1 citation)

II. **M. Fojtlín**, A. Psikuta, J. Fišer, R. Toma, S. Annaheim, M. Jícha, Local clothing properties for thermo-physiological modelling: Comparison of methods and body positions, Build. Environ. 155 (2019) 376–388. doi:10.1016/j.buildenv.2019.03.026. (0 citations)

III. **M. Fojtlín**, A. Psikuta, J. Fišer, R. Toma, S. Annaheim, M. Jícha, R.M. Rossi. Thermal model of an unconditioned, heated and ventilated seat to predict human thermo-physiological response and local thermal sensation, Build. Environ. Under review.

IV. **M. Fojtlín**, J. Fišer, M. Jícha, Determination of convective and radiative heat transfer coefficients using 34-zones thermal manikin: Uncertainty and reproducibility evaluation, Exp. Therm. Fluid Sci. 77 (2016) 257–264. doi:10.1016/j.expthermflusci.2016.04.015. (8 citations)

V. **M. Fojtlín**, J. Fišer, J. Pokorný, A. Povalač, T. Urbanec, M. Jícha, An innovative HVAC control system: Implementation and testing in a vehicular cabin, J. Therm. Biol. 70 (2017) 64–68. doi:10.1016/j.jtherbio.2017.04.002. (3 citations)

Each of the papers is a stand-alone publication consisting of an introduction focused on its individual topic, a detailed description of the methods, results containing figures and tables, a thorough discussion of the results, and conclusions with respect to the topic of the paper. Each publication presents original work that is an integral part of this PhD thesis. A commented over-view of the work with respect to the aim and objectives of this thesis is presented in Section 4.

4.3.1 The main author’s contribution to the publications

I. Conducted the majority of the experimental work, literature survey, data analysis, and writing of the manuscript.

II. Conducted the majority of the experimental work, literature survey, data analysis, and writing of the manuscript.

III. Contributed to the experimental study, developed the seat heat transfer model, carried out simulations with data analysis, and did the majority of the literature survey and writing of the manuscript.

IV. Conducted the majority of the experimental work, literature survey, data analysis, and writing of the manuscript.

V. Contributed to the iHVAC design requirements and experimental work, carried out the data analysis, and did the majority of the literature survey and writing of the manuscript.

5 SUMMARY OF THE WORK CONDUCTED

5.1 OBJECTIVE 1 (PAPER I): DETERMINATION OF CAR SEAT CONTACT AREA

For this work, the methods were divided into parts comprising collection of relevant previously published data from the scientific literature, original experimental measurements, and the development of a model to predict seat contact area using basic anthropometric descriptors (e.g. weight, height, BMI, and total body surface area). In the literature, two prevailing approaches to investigate seat contact area were found. One of the methods, presented by Wu [52] and McCullough et al. [53], consists of manually circumscribing a manikin placed on a seat. The second method, by Park et al. [50], uses dedicated pressure distribution sensors covering the seat surface.

Each method has its limitations, either in the precision (uncertain contact boarders in circumscribing) or in the equipment accessibility. Moreover, the studies presented only generalised results, which are not suitable for development of a seat contact regression model. Therefore, a novel method was proposed that utilised easily accessible tools, and consisted of generating prints of a human silhouette on fine paper placed on an automotive seat. The printed shapes were digitalized using a digital camera and processed in graphical software to obtain the surface area separately for the backrest and the seat cushion.

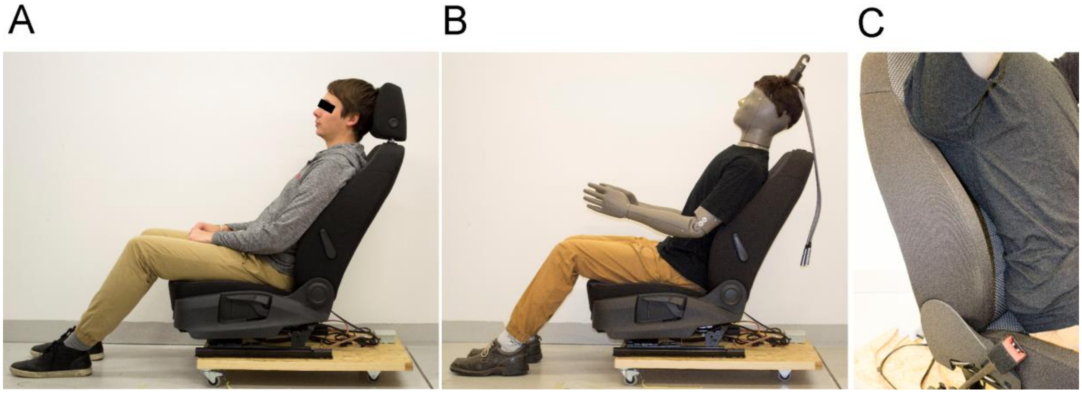


Figure 3. Illustration of the seating position. A human subject (A), the Newton manikin (B), and the detail of insufficient contact of the manikin's lower back with the back rest (C).

As shown in Figure 3, the actual prints were carried out on a sample of 13 participants covering approximately 82 % of the European population with regards to BMI (body mass index), ranging from the lower limit of normal weight (18.5 kg·m^{-2}) to the upper limit of overweight (29.4 kg·m^{-2}) [75]. To compare the contact area of human sample and a manikin, prints of the Western Newton-type thermal manikin (Thermetrics, WA Seattle, USA) were obtained using the same method. The seat for the investigation was selected from a middle-class passenger car, which might be likely equipped with a conditioning technology, such as seat heating and/or ventilation. Finally, the experimental results were compared to relevant scientific studies on human, manikin, and virtual manikin seat contact.

To assess the accuracy of the linear models, the coefficient of determination, R^2, and the root mean square deviation, RMSD, were calculated. The first parameter expresses the proportion of the variation in the dependent variable that is explained by the model. The second parameter is used to measure the average difference between measured and predicted values. To predict the accuracy of the slope and intercept of the linear model, a confidence interval for the best-fit line for the collected population with

95% was calculated. Finally, prediction intervals were calculated to estimate an interval in which future individual observations of the contact area will fall with 95% probability [76].

5.1.1 The summary of the main findings

The results of the study revealed a mean average contact that equals 18 % of the human body surface area. It was also confirmed that this surface area was in agreement with the virtual body geometry of the human thermoregulatory model FPCm5.3 at posterior parts of thorax, abdomen, hips, and upper legs. This finding is crucial in further utilization of the FPCm5.3 for reliable investigation of seat conditioning on human thermo-physiology and thermal perception using a heat flux density boundary condition. Thus, the same amount of heat exchange can be guaranteed in simulations as in humans under the same conditions.

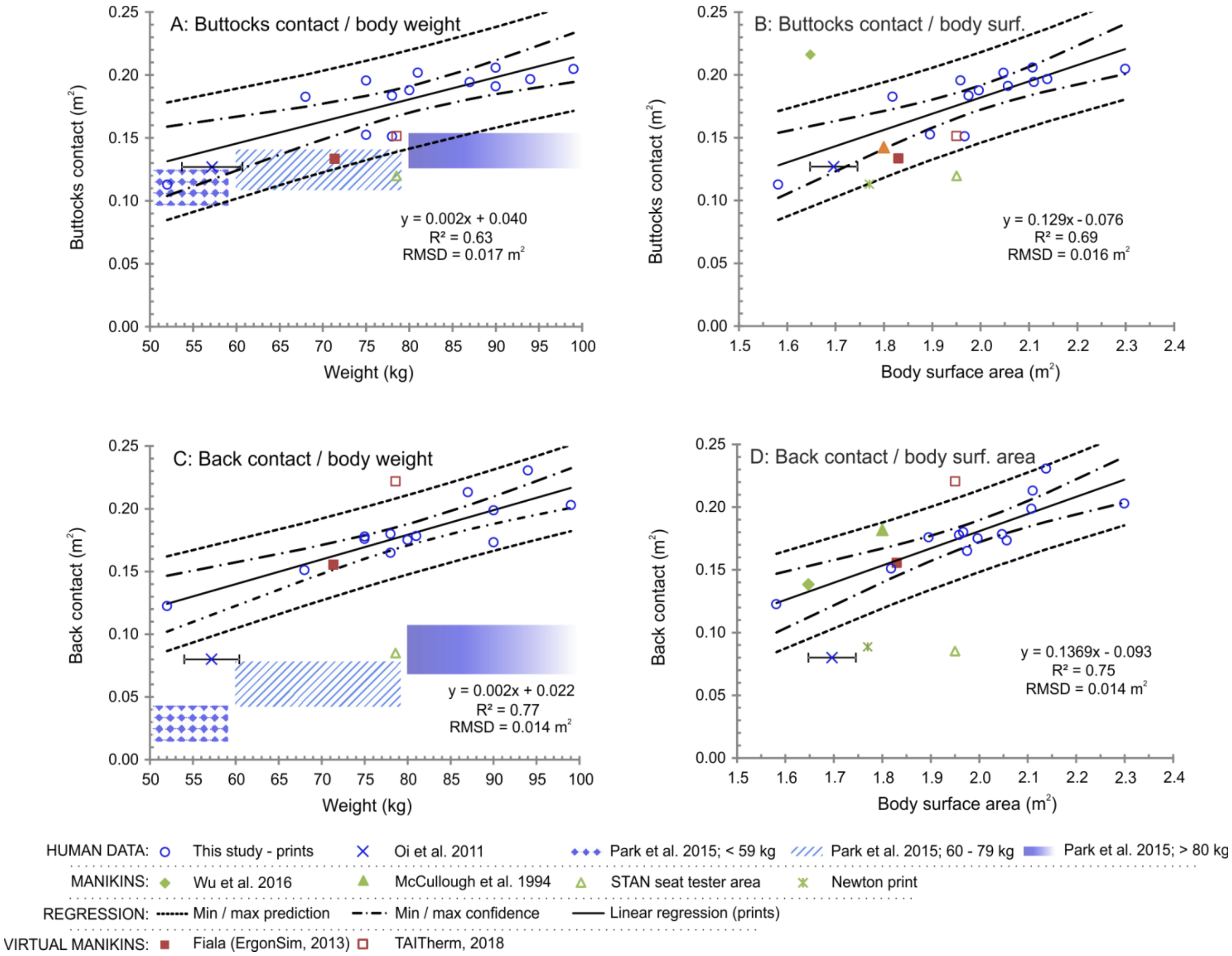


Figure 4. Local body contact areas. Contact areas at back and seat dependent on body weight (A and C), and total body surface area (B and D), respectively.

Four models to predict the total contact area based on human weight, height, body surface area, and BMI, respectively, were proposed. The best predicting capabilities were observed using two predictors, weight and body surface area, having the coefficient of determination of 0.86 and 0.83, respectively. Based on these findings, two models to predict the contact area for backrest (back) and seat cushion (buttocks), respectively, were developed using the weight and body surface area as two independent predictors

(Figure 4). The applicability of the models is restricted to the ethnicities of European descent as well as to the scope of examined anthropometric measures. There is indication that differences exist in the distribution of muscles and adipose tissues among ethnicities, which influence the resulting contact area. Finally, it can be expected that a plateau exists for higher values of BMI, as the seat reaches its maximal contact surface area

The cross comparison with data from literature revealed inconsistencies of using contemporary *hard shell* thermal manikins to investigate thermal effects of the seats. We found very limited applicability of thermal manikins in evaluation of seat contact area and their actual use with automotive seats. The seat contact area of the Newton type thermal manikin was found to be 35 % and 69 % smaller than that of a human at the seat cushion and backrest, respectively. These differences are due to the manikin´s low weight, rigid shell, and lack of spinal flexibility, which do not facilitate a human-like seat contact.

5.2 OBJECTIVES 2 AND 3 (PAPER II): CLOTHING THERMAL PROPERTIES

The focus of *Paper II* was examining the local clothing parameters in a sitting body position and the most probable ways of their determination. However, high precision results are typically dependent on access to costly equipment, such as thermal manikins and a climatic chamber. Therefore, it is of particular interest to identify an alternative solution with sufficient accuracy comparable to the state-of-the-art methods.

The summary of examined scenarios is presented in Table 1, organised in descending order of sophistication. We selected a range of methods based on manikin measurements, analytical heat transfer modelling [37,38], regression modelling [39], empirical modelling, such as the UTCI model [40], and ISO based approaches [28,41,42]. Additionally, differences in the local clothing values between sitting and standing body positions were investigated in detail.

Table 1 Summary of the examined scenarios to determine clothing thermal properties.

Case	f_{cl} (-)	I_{cl} ($m^2K.W^{-1}$)	$R_{e,cl}$ ($m^2Pa.W^{-1}$)	Position	Segments
1	3D scanning	Manikin heat loss [77]	Manikin heat loss [78]	sitting	13
2	Photography [28]	Manikin heat loss [77]	Manikin heat loss [78]	standing	13
3	Phys. model [37,38]	Phys. model [37,38]	Phys. model [37,38]	sitting	8
4	Phys. model [37,38]	Phys. model [37,38]	Phys. model [37,38]	standing	10
5	Regression model [39]	Regression model [39]	Phys. model [37,38]	standing	11
6	ISO based model [41]	ISO based model [41]	ISO based model [42]	standing	3
7	ISO Database [28]	UTCI model [40]	ISO Database [28]	standing	7
8	ISO Database [28]	ISO Database [28]	ISO Database [28]	standing	1

5.2.1 Clothing and definition of body positions

Since the research focus of this thesis was indoor environments, two ensembles were examined that correspond to the summer and winter seasons. The first clothing set represents summer indoor clothing (Figure 5B), consisting of a collar shirt, light cotton jeans, briefs, socks, and leather sneakers. The second, winter set comprised a turtle-neck shirt as well as a cotton T-shirt worn underneath, heavier cotton jeans, briefs, socks, and leather shoes (Figure 5C). All garments were selected from the database by Psikuta et al. [79] and were used throughout the study to guarantee consistency of the method.

The sitting body position was selected to mimic driving, operating machinery, or office work. The specifications were adopted from the work of Mert et al. [30] having an elbow angle of 120°, a hip angle of

110°, and a knee angle of 120°. Secondly, an upright standing position with hands down was examined since it is typically reported in the literature and was used to contrast the differences from one another.

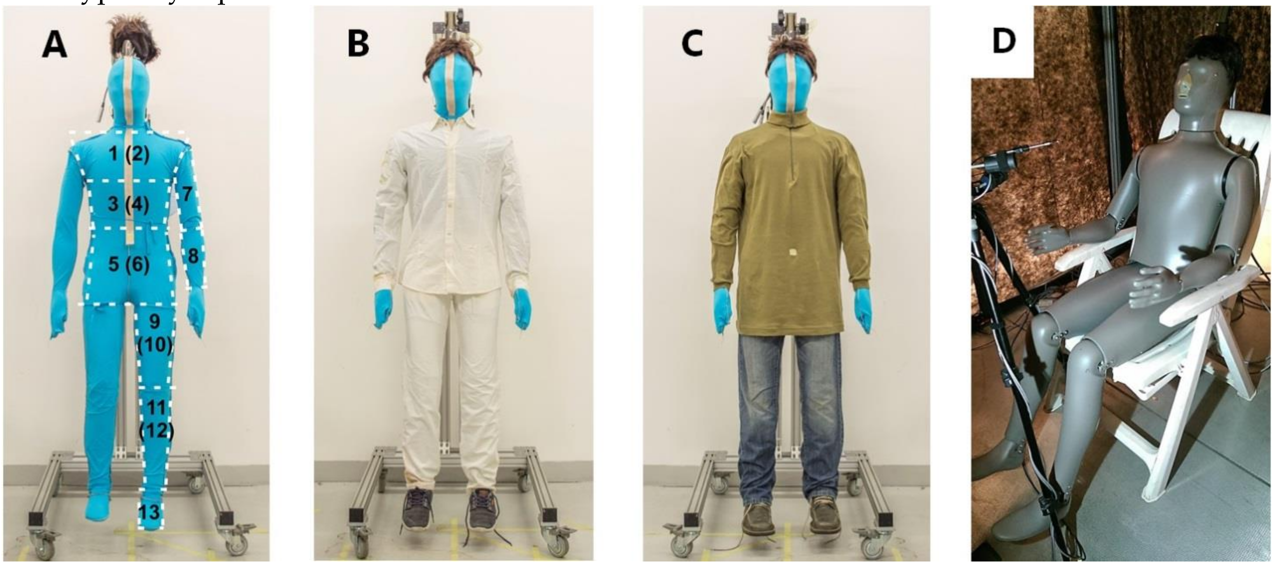


Figure 5. Illustration of the manikin and the clothing sets applied. A – segmentation of a nude manikin with an artificial skin, posterior parts in brackets; B – summer indoor clothing; C – winter indoor clothing; D – seated position. Note: segmentation from Figure 4A – 1 Chest, 2 Back, 3 Abdomen, 4 Lumbus, 5 Anterior pelvis, 6 Buttocks, 7 Upper arm, 8 Lower arm, 9 Anterior thigh, 10 Posterior thigh, 11 Shin, 12 Calf, 13 Foot.

5.2.2 Sensitivity analysis

Comparison of the absolute values of clothing thermal properties is beneficial for the process of clothing development. However, in practical applications, it is of major interest to understand the impact of such differences on the human thermal response, which may be dampened [62]. Thus, the eight cases were supplied to the FPCm5.3 in order to reveal their impact on the development of thermo-physiological parameters such as local skin temperatures, core temperature, sweat production, and skin wettedness as well as the global thermal sensation indicated by DTS (Dynamic Thermal Sensation). The environmental conditions were selected as thermo-neutral with the following characteristics: operative temperature summer case ($t_{air} = t_{rad} = 24$ °C), operative temperature winter case ($t_{air} = t_{rad} = 21$ °C), air speed of 0.1 m·s^{-1}, and relative humidity of 50 %. The metabolic production was selected with respect to the sitting body position as 1.3 met (driving or office work) and the simulations were carried out in a span of four hours with a five-minute simulation interval.

5.2.3 Summary of the main findings

The results of this study showed substantial variation among the methods for all examined clothing parameters, ranging from 13 – 43 % in f_{cl}, 35 – 198 % in I_{cl}, and 53 – 233 % in $R_{e,cl}$ of the reference value (Case 1). The most realistic results yielded the approaches based on analytical heat transfer modelling including realistic distribution of the air gaps (Case 3) [37,38] and the regression model (Case 5) [39] relating a garment ease allowance to the clothing insulation and clothing area factor. The least realistic approaches were the ISO based model (Case 6) [41,42] and the database values from the ISO standard itself [28]. The main reason for this lack of realism was a lack of method detail, in which the local values were lumped into larger areas, thus, neglecting the local extremes.

Altering the body position from standing to sitting causes a change in the orientation of several body parts and a redistribution of the air gaps. This also implies changes in all three clothing thermal parameters. While only minor changes were found for the global thermal and evaporative resistances [36], the local parameters showed much higher error margins:

- up to 31% of the reference value (*Case 1*) for f_{cl} depending on body part;
- up to 80% of the reference value (*Case 1*) for I_{cl} depending on body part;
- up to 92% of the reference value (*Case 1*) for $R_{e,cl}$ depending on body part.

There was a substantial influence of the discrepancies among the methods on predicted thermo-physiological responses. In mean skin temperature, the variation was within 0.6 °C and 1.3 °C in summer and winter clothing, respectively. This parameter is influential in thermal sensation models, where a considerable error in local thermal sensation can be expected in a range from 0.5 to 1.5 units depending on the thermal sensation model and its scale as demonstrated by Koelblen et al. [80] and Veselá et al. [81]. On the other hand, the differences in mean skin temperatures between the body positions were negligible, being within 0.3 °C.

The local thermo-physiological responses were clearly affected by the variation of the local clothing inputs. For example, relatively low differences in the clothing properties at the *chest* resulted in the absolute differences in skin temperatures of 0.5 °C among the methods and of 0.2 °C between the body positions. Quite the reverse, higher variability of input parameters, e.g. as at the *anterior thigh*, leads to a spread of the predicted local skin temperature of 1 °C and 2 °C in summer and winter clothing, respectively. The variability in input parameters also influenced the predicted amount of sweat as well as the onset of sweating. For instance, the sweat excretion amounted between 5 g (Case 7 winter clothing) and 138 g (Case 4 summer clothing) and the sweating onset varied between 60th (Case 8) and 190th minute (Case 7) using the winter clothing.

This study confirmed our hypothesis that the whole-body clothing properties are neither suitable nor sufficient for local thermal sensation modelling. Two non-experimental methods, physical and regression modelling, were recommended to substitute resource demanding manikin measurements for a variety of engineering applications. Finally, a sensitivity study revealed a dominant influence of the thermal insulation on the predicted thermo-physiological parameters. Therefore, to get a high-quality prediction of physiological responses in a sitting position, it is crucial to always choose the most reliable method to determine the local thermal insulation, respecting the body position.

5.3 OBJECTIVES 4 – 6 (PAPER III): CONDITIONED SEATS

Paper III addressed three major knowledge gaps in modelling of sitting exposures (Figure 6): (a) determination of heat exchange between the seat and its occupant; (b) validation of thermo-physiological responses under asymmetrical conditions induced by the seat; (c) prediction of thermal sensation under cold and hot environmental conditions using seat conditioning technologies such as seat heating and ventilation. Next, the findings from *Papers I* and *II* also contributed to reliable thermo-physiological simulations by determination of the seat contact area and by the use of the most accurate methods for determining the clothing thermal properties in a sitting body position.

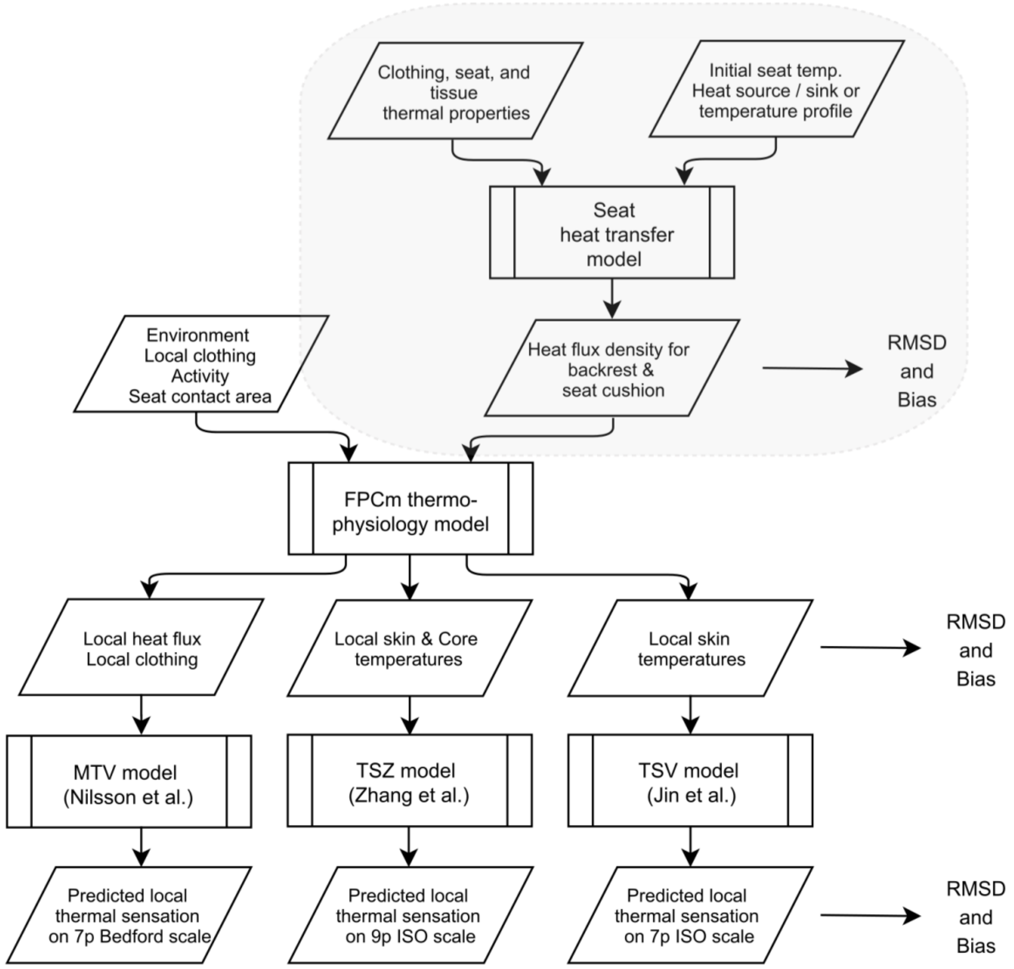


Figure 6. Overview of the methodology comprising the seat heat transfer model, FPCm5.3 model, and three thermal sensation models (references: MTV [68], TSZ [69,70], and TSV [72]). Highlighted parts were proposed in this study.

5.3.1 Development and validation of the seat heat transfer model

The seat heat transfer model was developed using the fundamental principles of heat transfer. The aim of the model was to provide sufficient approximation of the heat exchange between a seat with a considerable thermal mass and an adjacent body part such as the buttocks and back. A thermal system comprising human body tissues, clothing layers, and seat construction layers was designed and solved under the following presumptions:

- dominant heat flux in a direction perpendicular to the plane of the seat;
- neglected convection, evaporation, and radiation between the internal calculation nodes due to the high evaporative resistance of the seat and the negligible convection and radiation in the highly compressed layers of clothing and seat. Although the cooling in the ventilated seat is caused by sweat evaporation, in practical applications, it is not feasible to determine all necessary parameters for psychrometric calculations in the seat contact (e.g. air velocity, relative humidity, air temperature). The evaporative cooling was, thus, represented by a heat sink or a possibility to prescribe a temperature profile at the seat surface, yielding equivalent heat flux as if the evaporation was considered;

- neglected evaporation and radiation at the exterior calculation nodes (back of the seat) due to high evaporative resistance of the seat and partial shading of the back of the seat resulting in major simplification of the calculation;
- constant thermal properties of all human tissues, clothing, and seat construction layers;
- uniform thickness (but not the same) of all tissue, clothing, and seat construction layers;
- no thermoregulatory actions in the human tissues for a simplified solution; and
- solution using the finite-difference method with a discrete time step of 0.05 s.

The model yields calculated heat flux separately for the seat cushion and backrest. The model's validation was performed against original experimental measurements of heat flux, under cool (t_{air} of 18 °C) and hot (t_{air} of 41 °C) environmental conditions in the climatic chamber at Brno University of Technology. The validation procedure comprised unconditioned, seats heated to constant surface temperature, and ventilated seats. Details about the validation cases and participants can be found in Table 2, Cases 18 °C and 41 °C.

Table 2 Complete overview of the cases used for validation of the methodology

	Case	Pre-cond. 60 min t_{amb} (°C)	Chamber 30min t_{amb} (°C)	Seat conditioning	Males Uncond./ Cond.	Females Uncond./ Cond.	BMI M/F (kg.m^{-2})	Available data for validation
This study	18 °C	22.5	18	Uncond./ Heated const. temp.	8 / 14	2 / 6	25/23	8 skin temp.**; backrest & seat cushion temp. and HF; TS votes
	41 °C	25	41-25*	Uncond. / Ventilated	7 / 7	2 / 2	26/28	8 skin temp; backrest & seat cushion T and HF; TS votes
Oi et. al [51]	5 °C	22	5	Uncond./ Heated const. HF	8 / 8	-	18.6/-	Skin temp at backrest & seat cushion
	10 °C	22	10	Uncond./ Heated const. HF	8 / 8	-	18.6/-	Skin temp at backrest & seat cushion
	15 °C	22	15	Uncond./ Heated const. HF	8 / 8	-	18.6/-	Skin temp at backrest & seat cushion
	20 °C	22	20	Uncond./ Heated const. HF	8 / 8	-	18.6/-	Skin temp at backrest & seat cushion

t_{air} – ambient air temperature; BMI – body mass index; temp. - temperature, HF – heat flux density, TS – thermal sensation; *25°C reached after 20 min of exposure; **skin temperatures unavailable for unconditioned case

5.3.2 Coupling with thermo-physiological and thermal sensation models

In the next step, the seat heat transfer model outputs were coupled with the FPCm5.3 to obtain the predicted thermo-physiological response for the body parts in contact with the seat as well as for the rest of the body. Local skin temperatures were available for comparison to predictions at eight body sites (forehead, right scapula, left upper chest, right upper arm, left forearm, left hand, right anterior thigh, and left calf; segmentation from the ISO 9886:2004 [82]). To calculate mean skin temperature, the eight skin temperatures were averaged using the weighting coefficients from the standard [82].

The range of validation cases of the skin temperatures in the seat contact was extended using data from a paper by Oi et al. [51] at ambient temperatures of 5 °C, 10 °C, 15 °C, and 20 °C (details in Table 2). The seat used in the study was a front heated automotive seat. The heating was reported as a constant heat flux of 268 W·m^{-2} delivered both to the seat cushion and backrest [51]. The thermal interaction with the seat was modelled using the seat heat transfer model based on the description from the paper.

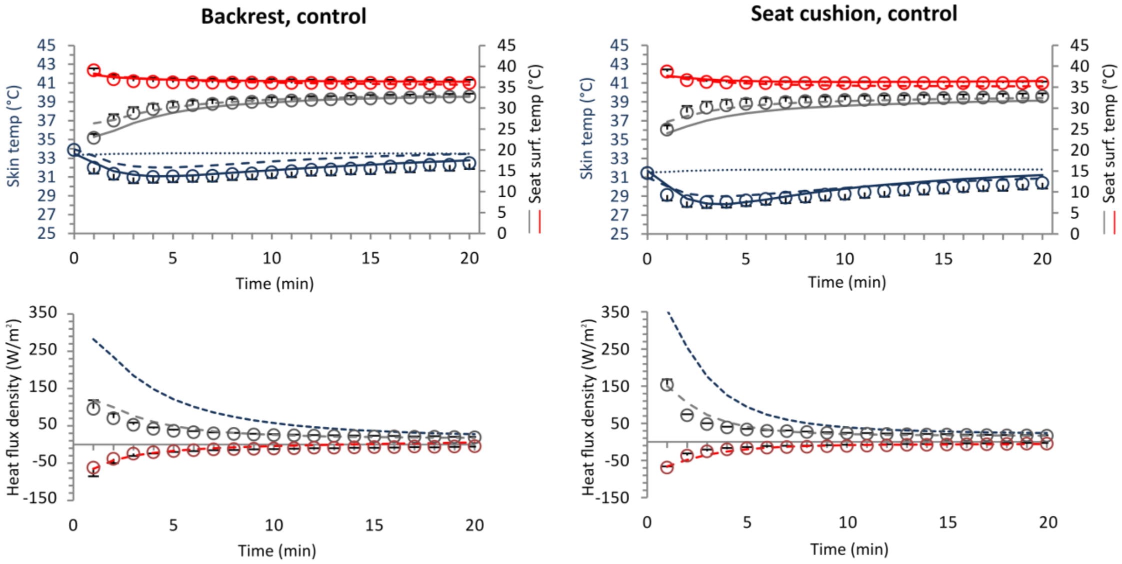
In the final step of this study, the thermo-physiological predictions were used to predict thermal sensation. In total, the performance of three local thermal sensation models was investigated: (a) model by Nilsson (MTV) [68]; (b) model by Zhang (TSZ) [69,70]; and (c) model by Jin et al. (TSV) [72]. In each step of the methodology, the accuracy of all predicted parameters (heat flux, seat temperatures, skin temperatures, and thermal sensation votes) was assessed by means of RMSD and bias. Predictions were assumed to have high precision if the RMSD and bias were within the standard deviation of the measurement.

5.3.3 Summary of the main findings

The proposed seat heat transfer model successfully predicted development of the heat fluxes at the seat-occupant interface (Figures 7-9). Throughout the exposure, the typical error of the calculated heat flux oscillated between 3 % and 10 % and the RMSD and bias were within two standard deviations of the measurement, with somewhat lower precision in the highly transient period after taking the seat. Psikuta et al. [83] stated that an error of 2 % has a negligible impact on the development of mean skin and core temperatures being less than ±0.18 °C and ±0.01 °C, respectively. Since the discrepancies in the predicted heat flux were close to these margins, a sufficient precision of the seat heat transfer model for coupling with FPCm5.3 was concluded.

Thus, in the next step, the seat heat transfer model was coupled with the FPCm5.3 to predict the temperatures in the contact with the seat as well as skin temperature in the non-contacting body part (Figures 7-9). Again, we found a good agreement between the predictions and measurements in terms the RMSD and bias. These findings were supported by the RMSD and bias being lower than the standard deviation of the measurement and, at the same time, within typical inter- and intra-human variations in skin temperatures (approximately 1 °C) [61]. Such precision is also sufficient for reliable thermal sensation modelling [80,81].

The benefits of the model were displayed against two simplified assumptions. For the unconditioned seat, the seat was assumed as thermal insulation and evaporative resistance (Figure 7). In the heated case, the seat was replaced with a heat generation boundary condition without dissipation to the ambient environment (Figure 9). These simplifications yielded not only four-times higher errors than that of the proposed methodology but also unrealistic development of the skin temperatures.



	Case	Backrest, control RMSD	Bias	SD	Seat cushion, control RMSD	Bias	SD
Contact temp. (°C)	5°C	0.3	-0.2	0.6	0.6	-0.5	0.7
	5°C *	1.9	-1.8	0.6	2.5	-2.4	0.7
	10°C	0.5	-0.5	0.5	0.7	-0.7	0.4
	15°C	0.4	-0.4	0.5	0.4	-0.4	0.6
	18°C	0.8	0.4	0.9	1.5	1.3	0.5
	20°C	0.2	-0.2	0.3	0.4	-0.3	0.6
	41°C	0.5	-0.4	0.9	0.5	-0.4	0.4
Contact heat flux (W/m²)	18°C	9.2	-3.3	2.9	8.1	-2.1	1.6
	41°C	12.6	10.0	7.6	3.5	1.5	3.5

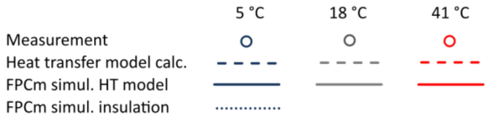
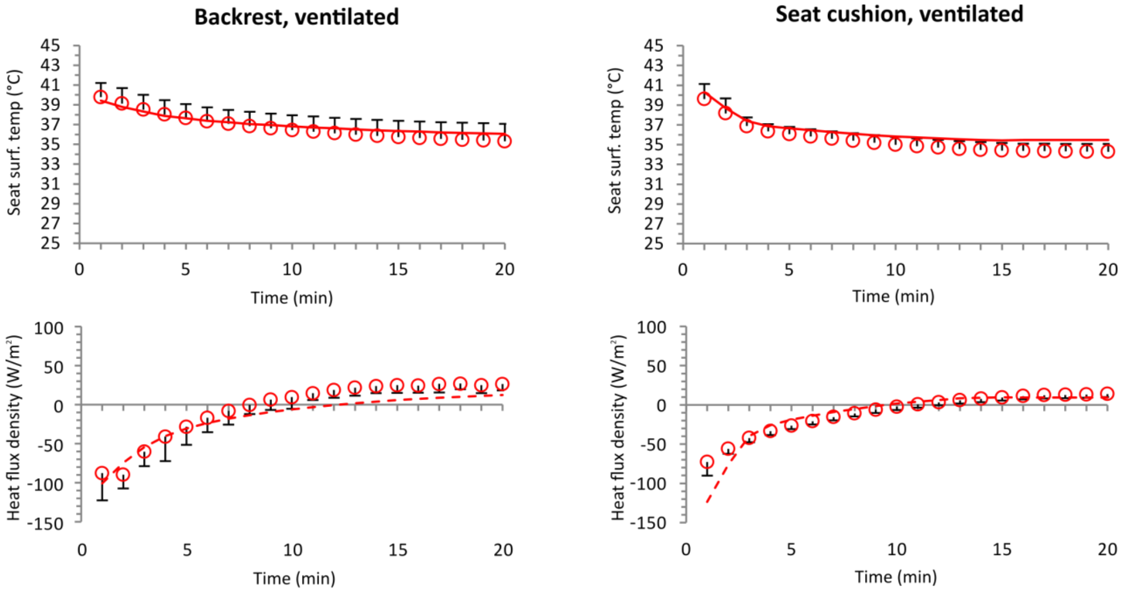


Figure 7. Unconditioned seats: skin (5°C case) and seat surface temperatures (18°C and 41°C cases), and heat fluxes (5°C, 18°C and 41°C cases) at the seat-body contact area. SD as error bars in the graphs. Seating at time 0 min. Case 5°C * depicts results of simulations where the seat was represented by insulation.



	Case	Backrest, ventilated RMSD	Bias	SD	Seat cushion, ventilated RMSD	Bias	SD
Temp. (°C)	41°C	0.6	-0.5	1.6	1.0	-1.0	0.9
HF (W/m²)	41°C	12.6	10.0	7.6	11.2	2.6	4.8

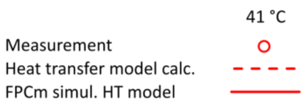
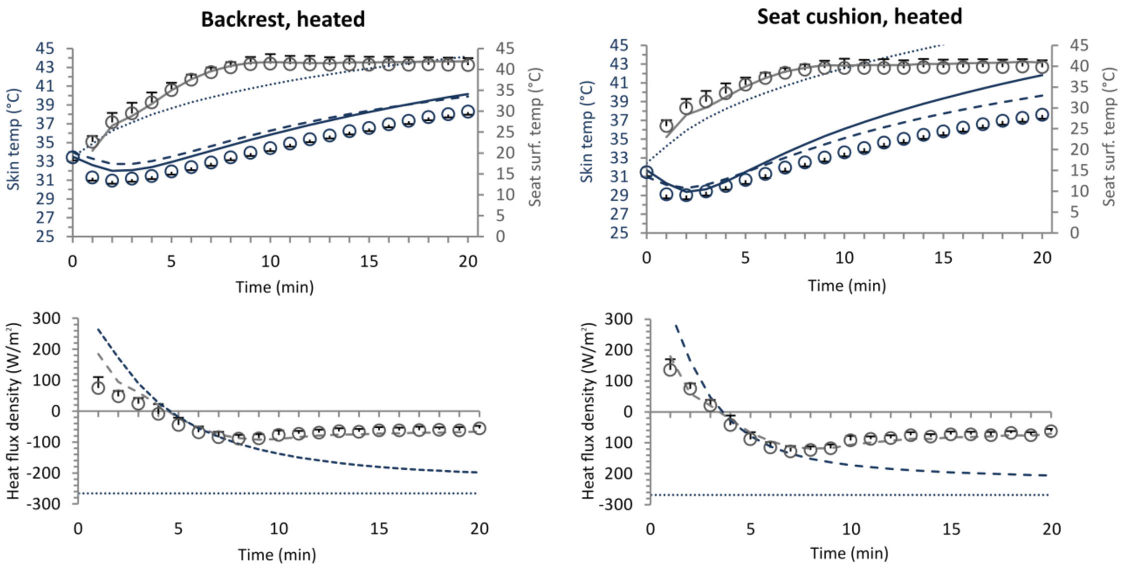


Figure 8. Ventilated seats: seat surface temperatures and heat fluxes in contact with the ventilated seat and the RMSD and bias for temperatures and heat fluxes from the FPCm5.3 simulations. The error bars depict standard deviation. Seating at time 0 min.



	Case	Backrest, heated RMSD	Bias	SD	Seat cushion, heated RMSD	Bias	SD
Contact temp. (°C)	5°C	1.4	-1.4	0.3	2.6	-2.3	0.4
	5°C *	6.2	-6.0	0.3	8.5	-8.3	0.4
	10°C	1.0	-1.0	0.3	2.5	-2.3	0.3
	15°C	1.4	-1.3	0.4	1.9	-1.7	0.4
	18°C	0.9	-0.5	1.8	1.2	-0.6	1.0
	20°C	0.2	-0.1	0.3	1.8	-1.6	0.4
Contact heat flux (W/m²)	18°C	7.9	4.7	13.1	12.2	-1.4	23.6

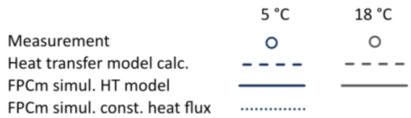


Figure 9. Heated seats: skin temperatures (5°C case), seat surface temperatures (18°C case), and heat fluxes (5°C and 18°C cases) at the seat-body contact area. SD as error bars. Seating at time 0 min. The 5°C * case depicts simulations, where the heated seat was represented by a constant heat flux applied to the skin.

The best performing thermal sensation models, in general, were MTV and TSZ, in which the RMSD and bias were within two standard deviations of the human votes having an average of 1.1 units. The two standard deviations of the thermal sensation votes were selected to cover 95 % of their dispersion due to the relatively low number of participants (details in Table 2). The worst performance was found in the TSV model. Here, the RMSD and bias exceeded two standard deviations in more than half of the body parts examined. Furthermore, TSV did not respond either to the temperature step change or to the cooling ramp, which is not acceptable in any application (Figure 10).

Although the skin temperatures were predicted accurately at the seat contact, the predicted thermal sensation was clearly less accurate than for body parts without seat contact. Since the TSZ contains a derivative component, it performed well in the transient conditions (the first six minutes of the exposure), with an RMSD and bias within two standard deviations. Nevertheless, after this period, TSZ drifted towards higher thermal sensation votes and exceeded the two standard deviations limit. In the first six minutes of the cool exposure, the MTV model tended to over-estimate the effects of the cold seat by up to 2.3 units. This error was mainly because of the high initial cooling rates (up to 150 W·m^{-2}) and no derivative component of the model. The remaining part of the cool exposure (18 °C) typically followed the trends of the experimental data. Under hot conditions, on the other hand, the accuracy of the predictions by MTV was the best out of the three models, having the RMSD and bias of approximately one standard deviation.

The lower accuracy of the thermal sensation predictions in the contact can be attributed to several dominant factors. Firstly, the range of temperatures that can occur during contact is wider than that without contact. Thus, the thermal sensation models were at or beyond their limit of applicability. Next, Oi et al. [51] concluded that comfortable skin temperatures at the seat contact are higher by lower ambient temperatures, what can influence thermal sensation voting and acceptability of locally higher skin temperatures. Similar findings were also demonstrated by Zhang et al. [84] for heated and cooled seats in a range of ambient temperatures of between 15°C and 45°C. Nevertheless, none of the examined models captures this dependence. For the aforementioned reasons, further refinement of current thermal sensation models is needed to achieve more consistent predictions.

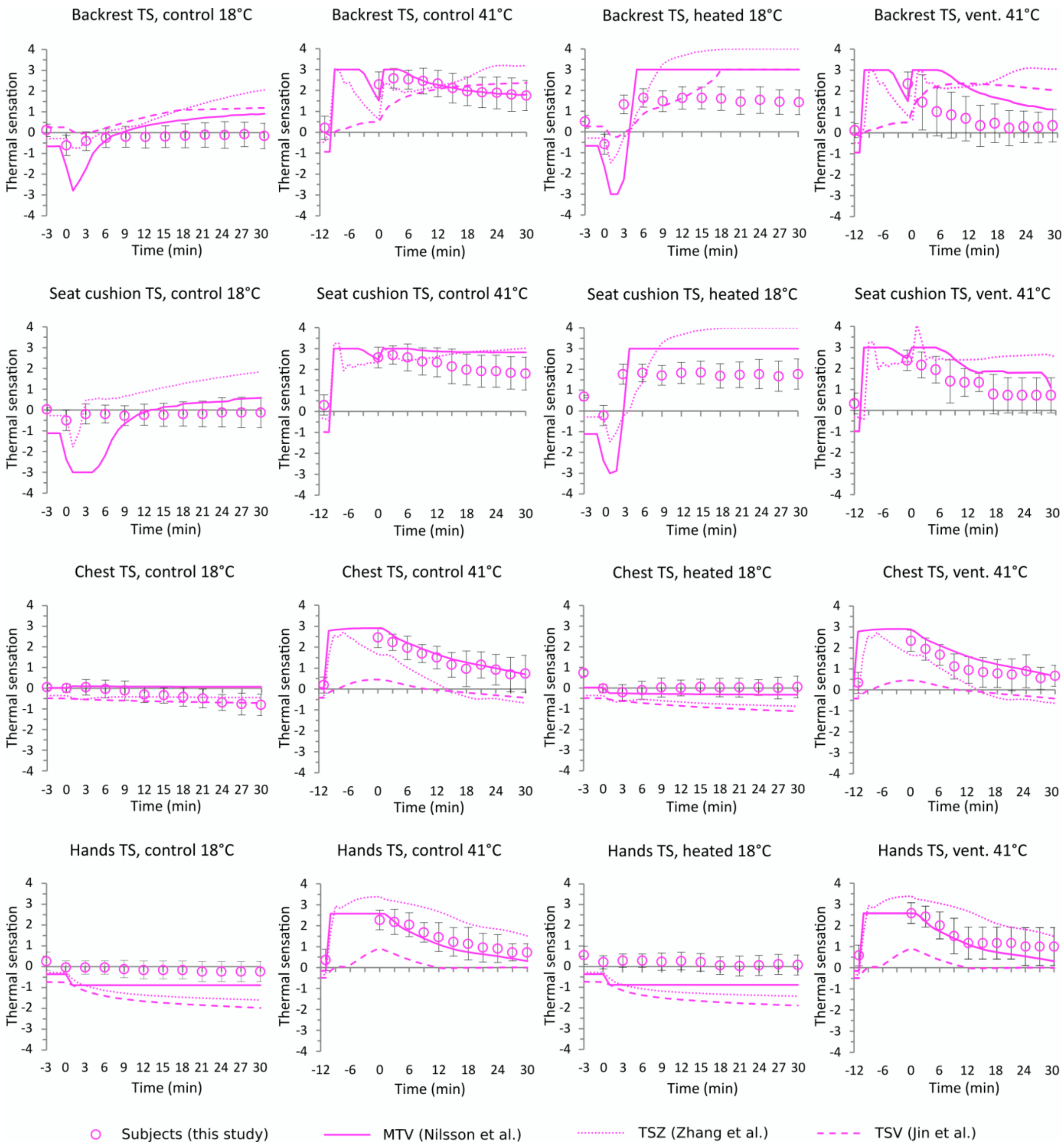


Figure 10. Thermal sensation votes at the seat cushion (posterior thighs and pelvis), backrest (posterior thorax and abdomen), hand and chest. Predicted by three thermal sensation models. SD shown as error bars. Note that MTV uses a seven-point Bedford scale, TSZ uses a nine-point ISO scale, and TSV uses a seven-point ISO 10551 scale.

5.4 OBJECTIVES 7 – 8 (PAPERS IV AND V): HARDWARE DEMONSTRATOR

In this part of the thesis, we examined the idea to develop a hardware demonstrator consisting of several cost-effective equivalent temperature sensors and their integration into a vehicular cabin in proximity of an occupant. The demonstrator is aimed to be an integral part of the cabin interior, rather than a manikin or a dedicated laboratory instrument. The spatial distribution of the directional equivalent temperature sensors was expected to provide detailed information about the local effects of the environment on the occupant. Further, the equivalent temperature was shown correlate with thermal sensation [68,85] (see Section 2.2.4) and thus, could be translated into a local thermal sensation vote. Such system input could be used to evaluate thermal sensation in real time and serve as a basis for thermal-sensation-driven HVAC control.

5.4.1 Evaluation of the manikin measurement uncertainty

The Newton-type manikin was used for the calibration of the equivalent temperature system in the actual cabin environment. However, no detailed statistical analysis of repeated manikin measurements was available. For this reason, we carried out a study on measurement uncertainty of the Newton-type manikin in typical laboratory conditions in both sitting and standing position (*Paper IV*). The experimental data were obtained from three independent repetitions of measurements in steady conditions inside a climatic chamber with a calibration box to ensure homogenous environmental conditions. A series of tests were carried out to reveal statistically significant differences (95% confidence) among repeated measurements of radiative and convective heat transfer coefficients as follows:

- Kolmogorov-Smirnov test for normal distribution of data. Normality is a fundamental premise for the calculation of succeeding tests. The assumption of normality was satisfactory for all cases except for the head;
- Bartlett test for homogeneity of variances. Homogeneity is accepted if the variances of studied populations are sufficiently equal. This criterion is also essential premise for the test for the means. The assumption of homogeneity of variance was satisfactory for most of the body parts, but not for the posterior forearms, upper thighs, and calves; and
- Test for the means using one-way ANOVA. The test revealed statistically significant differences of the means for most of the body parts. Therefore, A and B type uncertainty evaluation was further expressed.

The A type uncertainty evaluation represents a statistical analysis of series of independent observations having normal distribution. The typical expanded uncertainty (95% confidence level) was found below 8 % of the mean. The B type uncertainty is determined by means other than statistical analysis of series of independent observations. It is a function of partial uncertainties that enter the calculation of the studied physical value (e.g. measurement of air and manikin’s surface temperatures, heat flux etc.) [86]. The typical expanded uncertainty (95% confidence level) was found below 4 % of the mean. These findings are in line with other manikin studies and are within boundaries for reliable manikin applications [59]. Therefore, we found the Newton-type manikin suitable for calibration of the equivalent temperature system.

5.4.2 Development of the hardware demonstrator

The modular system of equivalent temperature sensors was designed and produced (Figure, 12; full description in *Paper V*) based on the criteria defined by their intended application:

- precision of temperature measurement and heating stability better than 0.1°C;
- sufficient heating power to start up from temperature of -20 °C within 2 minutes – achieved by maximal heating power of 1000 $W \cdot m^{-2}$;
- stable control in the typical conditions, approximately from 20 to 100 $W \cdot m^{-2}$;
- small size (20 × 20 × 10 mm) allowing unobtrusive installation in the cabin; and
- system modularity, with the ability to add or remove an arbitrary number of sensors

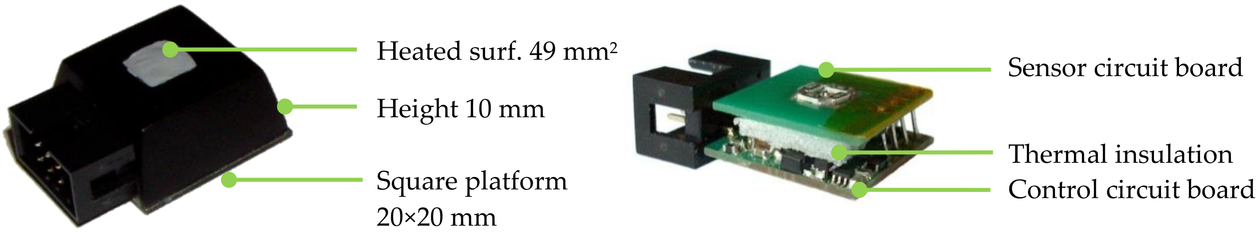


Figure 11. Detail of the equivalent temperature sensor and bare sensor on the right.

5.4.3 Integration of the demonstrator into the cabin

Sixteen t_{eq} sensors were distributed in the vicinity of the driver to capture the orientation of 16 body parts (*Paper V*, Figure 2). Nevertheless, the optimal placement and orientation of the sensors was in some cases restricted. This was most critical for upper and lower limbs, where the sensors could not be placed with the same spatial orientation. To mimic segmental equivalent temperature (such as output from a manikin) one or more sensors were allocated in an aggregation map to each body part. The aggregation map served as a platform, in which the individual signals were scaled (calibrated) according to the manikin measurements under the same conditions.

To eliminate weather disturbances from the ambient environment, the calibration was carried out in climatic chamber conditions under three basic conditions:

- A cold case, 10°C, no solar irradiation;
- Neutral case, 20°C, no solar irradiation;
- Hot case, 25°C, solar simulator 700 W/m^2, 70° elevation, facing the left side of the car.

The calibration procedure began with a preconditioning of the experimental vehicle in a climatic chamber until stable conditions in the cabin were reached. At the same time, the Newton-type manikin was seated at the driver's seat and was operating with a constant surface temperature of 34 °C. Next, the vehicle was started and the proposed system of equivalent temperature sensors was initiated. The cabin microclimate was managed by the on-board HVAC system, which was set to a control regime 'Automatic 22°C'. Each trial lasted for one hour and for the calibration purposes, the last five minutes of the measurement period were evaluated. All the examined cases were pooled to find optimal scaling coefficients for the aggregation map. To do so, the differences between the equivalent temperature obtained from the manikin and the system were minimized by the GRG (Generalized Reduced Gradient) optimization scheme.

5.4.4 Summary of the main findings

In steady conditions and at the majority of body parts, the system of equivalent temperature sensors was capable of determining the t_{eq} with precision better than 1 °C. In cold conditions, the system underestimated t_{eq} by 1.9 °C for the lower legs. Conversely, in neutral conditions, the system overested t_{eq} by 1.8 °C for the anterior thighs. In hot conditions, the prediction accuracy of the system was the highest. In general, the limbs are the most challenging body parts to determine their corresponding equivalent temperature using the flat-surface sensors. It is because of their cylindrical shape and positioning in the cabin. Next, the sensors were not equipped with guarding (heated) surfaces that would prevent lateral heat losses from the measurement surface to the body of the sensor. The guarding was substituted by thermal insulation, but this was not sufficient since we found a decreasing trend in the accuracy of the measurement with decreasing ambient temperature. At the same time, guarding is essential for examination of rapid changes in t_{eq} to avoid the influence of the thermal capacity of the sensor's body.

The comfort zone diagram by Nilsson [68] is used to relate the equivalent temperature to mean thermal vote of a given body part. The *width* of the zones depends on the clothing and body part sensitivity. However, to cross one zone, such as to go from hot but comfortable down to cold but comfortable, a difference in the equivalent temperature of at least 3 °C is needed. For this reason we concluded sufficient precision of the demonstrator for its further applications.

6 CONCLUSIONS

As formulated in the objectives, this project presents a model to calculate seat contact area; clothing thermal properties in a sitting body position; method to address local seat conditioning; and a physical demonstrator integrated into a cabin. This PhD thesis has demonstrated the applicability of certain methods to predict thermal sensation in a sitting body position with regards to the respective factors typical of vehicular-cabin environments.

The summary of the main conclusions from individual studies is as follows:

- the seat contact area of an average person is approximately 18 % of the total body area;
- The seat contact area in FPCm5.3 can be realistically represented by posterior parts of the thorax, abdomen, hips, and thighs;
- within a range of the typical European population, the seat contact area can be described using linear equations and predicted based on weight and/or total skin surface;
- thermal manikins without adjustments are not suitable for research in seat contact;
- two-fold differences exist in local clothing thermal properties between the standing and sitting positions and these differences have substantial impact on local predicted thermo-physiological responses;
- physical modelling with a realistic air-gap distribution and regression modelling was found to be sufficient for replacing the state-of-the-art measurements of clothing thermal properties. This applies to indoor (*office*) clothing for summer and winter season;
- the seat heat transfer model significantly contributed to the improvement of predicted thermo-physiological responses and thermal sensation for the contact body parts;

» uncertainty of the Newton-type thermal manikin was defined and was found sufficiently accurate to be used for calibration of the on-board t_{eq} measurement system; and

» the t_{eq} measurement system was shown to determine equivalent temperatures for individual body parts in the cabin to the precision of ±1°C.

The knowledge gaps addressed in this thesis were mostly related to the quality of input parameters and extension of the applicability of already existing methods. This brought the modelling approach much closer to realistic applications and tackling challenges in engineering, rather than creating "just another" model of thermal sensation or thermo-physiology. The engineering community can benefit from the prompt calculations of both physical variables and consequent subjective thermal sensation for a given environment with a known error. This ability for rapid calculation enables the effective evaluation of human interactions with indoor spaces, reducing the dependence on costly, logistics-intensive, and labour-intensive human subject studies.

6.1 FUTURE PERSPECTIVES

One of the most influential contemporary motivations for thermal comfort research is to efficiently create comfortable and healthy conditions with respect to low energy consumption and other environment impacts. These demands are still conflicting. However, the proposed methodology can be used to carry out parametric studies focused on investigating strategies to mitigate the energy consumption using local conditioning technologies or by changing the construction of the cabin (e.g. altering the position of air inlets, glazing, and shading). Such knowledge is of major interest in the field of battery powered electric vehicles, where the microclimate management operates at the cost of driving range.

The system of inexpensive equivalent temperature sensors demonstrated an opportunity to shift traditionally laboratory based equipment into a consumer market. In asymmetric and transient thermal environments, such a device can be used for personalisation of the thermal experience and zoning with much higher accuracy than any commercially available solution. Furthermore, the user can define his/her thermal expectation from the HVAC system in more natural way, via a desired thermal sensation for individual body parts, rather than a desired ambient temperature. This would likely lead to an enhanced thermal experience and higher thermal comfort. Indeed, it was shown that the psychological aspect of having control over the environment automatically improved satisfaction with the indoor conditions [23,24].

Additionally, computational methods can be also used for academic purposes. Here, the thermo-physiological model with realistic input data can be applied to reconstruct studies from the literature as well as field-based studies where thermal sensation was investigated, but no thermo-physiological data were collected. Very often, this is the case because specialised equipment and approval of an ethical board is needed to carry out research with human participants. Therefore, such efforts would contribute to extending the pool of exposures and could serve as a basis for refinement of local thermal sensation modelling.

6.2 LIMITATIONS

The complexity of the mechanisms behind human thermal perception is much higher than the contemporary understanding. Because of this, many parameters influencing thermal perception are not considered by the models. Thus, the major weakness of thermal sensation modelling is still a generalisation of the results, which cover only a certain population and certain conditions with typical accuracy better than one thermal sensation unit.

The predictive power of the examined thermal sensation models was lowest at the body parts in contact with the seat. The range of skin temperatures under seat contact is much wider than the rest of the body exposed to the ambient conditions, either because of the initial seat temperature or because of the seat conditioning. Moreover, in highly asymmetric conditions, the local exposure may significantly affect local thermal sensations of an unexposed body parts [87] and comfortable skin temperatures are higher with lower ambient temperatures [51]. However, none of the examined models captures these effects and subsequent extension is required.

The proposed seat heat transfer model was developed to calculate realistic heat exchange between the seat and its occupant. In order to reduce number of input parameters and, at the same time, potential sources of uncertainty, the cooling effects of latent heat of sweat vaporisation was replaced by a heat sink or a possibility to prescribe a time-dependent temperature profile at the seat surface, yielding equivalent heat flux as if the evaporation was considered. While thermal sensation models require only inputs such as skin and core temperatures or heat flux, the neglect of the water propagation restricts the investigation of discomfort induced by skin wetness.

Finally, several limitations of the method should be noted for the hardware demonstrator. The equivalent temperature approach captures the sensible heat only. This might not be sufficient for hot conditions where a larger amount of sweat is likely to be excreted by a human body and, thus, evaporation starts to play a dominant role in cooling. In such case, the predictions would be inaccurate. Next, in hot conditions, the method can be used only up to the temperature of the heated surface. Beyond this limit, the sensor receives heat from the ambient environment and is no longer capable of heat flux measurements. On the other hand, Nilsson [74] commented that the sensor could be used in a passive thermometer mode, when the surface temperature can be approximated to the equivalent temperature. Finally, this methodology is applicable under transient ambient conditions. However, a transient state can arise also on the side of the human with regards to metabolic heat production and prior environmental exposures. Under human-centred transients, it is likely to see a substantial error in predictions of thermal sensation.

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Work experience

PhD project, full time **06/2017 – 12/2018**
Swiss Federal Laboratories Empa, St. Gallen, Switzerland
- Established a methodology for virtual investigation of ventilated and heated seats
- Conducted and co-organised experiments with human subjects
- Wrote three peer-reviewed scientific publications

Junior researcher, part time **10/2012 – 04/2017**
Škoda Auto a.s., Brno & Mladá Boleslav, Czechia
- Implemented a methodology to determine clothing thermal properties
- Participated in implementation and testing of innovative vehicular HVAC systems
- Gained experience with state-of-the-art measurement equipment

Junior constructor, full time **12/2011 – 09/2012**
OMS lighting, Dojč, Slovakia
- Modified existing products based on a customer's demand
- Prepared 3D models and drafts in Catia V5

Education

PhD program - Construction and Process engineering **09/2014 – present**
Brno University of Technology, Brno, Czechia
- Expanded knowledge in the assessment of thermal environments in vehicles
- Focused on methods allowing for rapid virtual testing of HVAC solutions

Master's program in Environmental engineering **09/2012 – 06/2014**
Brno University of Technology, Brno, Czechia
- Gained theoretical knowledge in Heat transfer, Energy machinery, and HVAC
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Skills

Skills
- Experimental work
- Scientific writing
- Presentation
- MS Word & Excel
- Matlab, CAD & CFD

Languages

Slovak & Czech	Native
English	Full
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Strengths

Logical thinking · Team-working · Creativity · Patience · Adapting

Personal interests

Electric Mobility · Sustainability · Photography · Mountain Biking · Running

Awards

Dean's award for the excellent master's thesis
06/2014
Brno University of Technology
https://www.sciencedirect.com/science/article/pii/S0894177716300917
- Extended the laboratory know-how in precise thermal manikin measurements

3rd Oral Presentation Prize
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- Presented a demonstrator of the Innovative HVAC control system to a international expert audience

ABSTRACT

People in developed countries spend substantial parts of their lives in indoor environments both during free time and while working. For this reason, there has been increasing interest in the quality of the indoor environment. The main emphasis of past research has been directed towards understanding the fields of human health, productivity, and comfort. One important contributor to all three fields is the thermal aspect of the environment, which is often represented by physical quantities such as air temperature, radiant temperature, air humidity, and air velocity. While weather-independent control of these parameters is possible via heating, ventilation, and air-conditioning systems (HVAC), a major limitation is that these systems are related to substantial energy consumption and carbon footprint. The complexity of thermal management is amplified in vehicular cabins because of their asymmetric and transient nature. Moreover, in electric vehicles, the available energy for microclimate management comes at the cost of driving range, and therefore, new solutions for more effective and human-centred ways of managing the indoor microclimate are sought.

One of the promising ways to address these issues is via local conditioning with the vehicle seats or auxiliary radiant panels operating in synergy with an HVAC unit. At the same time, the optimization and research tasks are being shifted towards virtual investigation to mitigate the need for costly and often ethically concerning human studies. To do so, models of human thermo-physiology and thermal sensation/comfort have been developed. Yet, for their reliable applications, many factors regarding high heterogeneity, clothing, the thermal mass of the adjacent surfaces, and active seat conditioning have not been resolved.

The aim of this thesis was to develop a methodology to assess human thermal sensation while in a sitting body position, including local conditioning factors such as heated and ventilated seats. A requirement of the method was applicability in both virtual and real indoor spaces. In the latter case, the focus was a thermal-sensation-driven feedback loop allowing for human-centred microclimate management.

The validity of the proposed methodology was demonstrated under typical cabin conditions (5–41 °C) and the findings from this PhD project are transferable to a broad variety of engineering fields. In passenger transport and occupational environments with higher heat strain, environmental engineers can benefit from a tool to identify sources of thermal discomfort and potential hazards of fatigue. Furthermore, the methodology can be of great merit to the rapidly developing electric vehicle industry, facilitating emphasis on energy efficient microclimate management. The virtual optimization of the conditioning strategies reduce the need for human studies, allow rapid prototyping, and have great potential to bring energy savings as well as increased driving range. Finally, the know-how presented is also applicable in built environments, where similar conditions apply.

ABSTRAKT

Ľudia žijúci vo vyspelých krajinách trávia väčšinu svojho života vo vnútorných prostrediach budov alebo dopravných prostriedkov. Z tohto dôvodu, záujem o výskum kvality vnútorných prostredím rastie, pričom hlavný dôraz je kladený na oblasti výskumu ľudského zdravia, produktivity a komfortu. Jedným z faktorov ovplyvňujúci kvalitu prostredí je ich tepelný aspekt, ktorý je najčastejšie popísaný teplotou vzduchu, radiačnou teplotou, vlhkosťou vzduchu a rýchlosťou prúdenia vzdu-chu. Zatiaľ čo tieto parametre je možné riadiť systémom pre vykurovanie, vetranie a klimatizáciu nezávisle na počasí, takéto zariadenia sa podieľajú na vysokej spotrebe energie a značnej uhlíkovej stope. V prostediach kabín áut a dopravných prostriedkov je riadenie parametrov tepelného prostredia komplikované z dôvodu ich asymetrickej a časovo premenlivej povahy. Táto situácia je obzvlášť kritická vo vozidlách na elektrický pohon s vlastnou batériou, kde je energia na úpravu vnútornej mikroklímy čerpaná na úkor dojazdu vozidla. Pre uvedené dôvody sa hľadajú nové, energeticky účinnejšie spôsoby pre úpravu tepelných prostredí a zabezpečenia tepelného komfortu.

Jedným z potenciálnych riešení sú zariadenia dodávajúce človeku teplo alebo chlad lokálne, ako napríklad vyhrievané a vetrané sedadlá a sálavé panely. Vzhľadom na to, že experimentálny výskum vnútorných prostredí je náročný s ohľadom na čas a potrebné vybavenie, trendy výskumu vplyvov takýchto zariadení na človeka smerujú k optimalizačným úlohám vo virtuálnych prostrediach pomocou modelov ľudksej termofyziológie a tepelného pocitu/komfortu. Avšak pre spoľahlivé výsledky modelovania sú potrebné presné vstupné parametre definujúce prostredie, odev, vplyv povrchov v kontakte s človekom (napríklad sedadlá) a pôsobenie systémov na lokálnu úpravu mikroklímy.

Cieľom tejto dizertačnej práce je vytvorenie metodológie na hodnotenie tepelných prostredí v kabínach automobilov s ohľadom na pozíciu v sede a využitím technológii na lokálnu úpravu tepelných prostredí. Jedným z požiadavkov na takúto metodológiu je jej aplikovateľnosť vo virtuálnych ale aj reálnych prostrediach. V prípade hodnotenia reálnych prostredí, cieľom je vytvorenie demonštrátora, ktorý by bol využiteľný ako spätná väzba pre riadenie systémov pre úpravu mikroklímy na základe požadovaného tepeleného pocitu.

Validita uvedenej metodológie bola demonštrovaná v typických podmienkach kabín automobilov (5–41 °C) a poznatky z tejto práce sú prenesiteľné do širokého spektra inžinierkych aplikácii. V oblasti osobnej dopravy a pracovných prostredí s vyššou tepelnou záťažou je táto metóda užitočná pre identifikáciu možných zdrojov diskomfortu. Navyše je táto metóda vhodná i pre rýchlo rastúci segment elektrických vozidiel, kde je možné sledovať tok energie potrebnej na dosiahnutie určitej úrovne komfortu a riešenie optimalizačných úloh za účelom úspory energie a predĺženie dojazdu. Obdobné aplikácie možno nájsť i v budovách a prostrediach s podobnými charakteristikami.