A Multi-Domain Approach to Explanatory and Predictive Thermal Comfort Modelling in Offices

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Abstract. It is well known that physical variables, such as temperature, exert a significant influence on occupants' thermal comfort in office buildings. Despite this knowledge, models that are currently used to predict thermal comfort fail to do so accurately, resulting in a mismatch between design conditions and actual thermal comfort conditions. The assumption is that exclusive attention to physical variables is insufficient for understanding or predicting thermal comfort. Contextual, social and personal variables may also affect thermal comfort in office buildings and interact with each other. The question arises as to how a multi-domain approach can aid in explaining and predicting thermal comfort in offices. In this study, a unique dataset containing indoor environment, demographic, occupancy and personality related variables is used to construct two types of thermal comfort models. The dataset contains 524 observations, collected during summertime in two office buildings in the Netherlands. Firstly, structural equation modelling (SEM) is used to construct an explanatory model, with the aim to identify significant variables affecting thermal comfort, as well as the interactions between them. Secondly, machine learning is used to train four binary classification models to predict thermal discomfort. For the investigated cases, SEM suggests that thermal discomfort is significantly affected by (i) temperature, (ii) sound pressure level, (iii) the interaction between temperature, sound pressure level and illuminance, and (iv) the interaction between gregariousness and occupancy count. The four predictive models are subsequently trained using only the significant variables. Nevertheless, the weighted F_1-score for all four models ranges between 0.55 and 0.59, indicating weak predictive performance. The results show that significant influencers are not necessarily good predictors of thermal discomfort. Future researchers are encouraged to combine explanatory and predictive modelling techniques, in order to test whether variables that are relevant to the domain are useful for prediction.

Keywords. Thermal comfort, multi-domain, personal domain, interaction effects, structural equation modelling, machine learning.
DOI: https://doi.org/10.34641/clima.2022.181

1. Introduction

Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment [1]. Building engineers refer to building standards to predict the thermal comfort conditions for a given design [1,2]. However, current standards do not always produce adequate thermal comfort predictions [3]. For example, the most prominent model for predicting thermal comfort in office buildings, Fanger's PMV, does not consider the influence of non-thermal influences and does not account for interactions between influences [4]. Recent research efforts have focused on multi-domain approaches that treat thermal comfort as a combination of variables belonging to four domains, which are outlined in **Fig. 1** [5].

1.1 research background

Researchers in the field of thermal comfort seek to understand and predict thermal comfort. The former deploy explanatory models, while the latter use predictive models. Explanatory models typically employ statistical techniques that provide insight into what influences thermal comfort in offices. Predictive models are built to forecast the thermal comfort conditions for a given office space. The relevance of social, contextual and personal factors is apparent but their presence in existing thermal comfort models is limited [6]. The combined presence of all four domains is almost non-existent [6]. Moreover, the majority of existing studies focus on explanatory modelling [6]. As a result, the research community has yet to identify a prominent multi-domain model for predicting thermal comfort in offices. The absence of a comprehensive predictive model causes stagnation in the engineering sector, as building engineers rely on sub-optimal models to meet thermal comfort regulations.

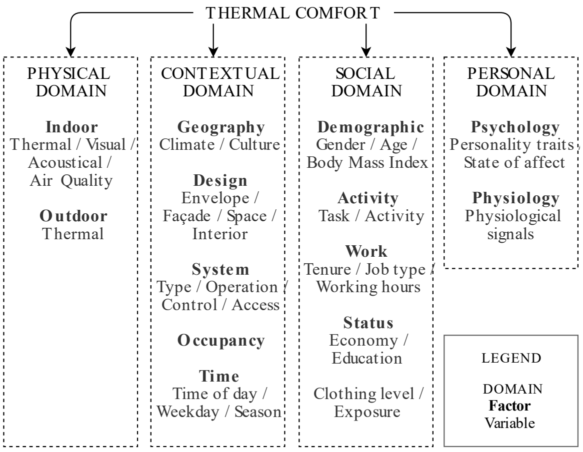

Fig. 1 - Physical, social, contextual and personal variables present in literature, adapted from [5].

The rift between design conditions and real-world thermal conditions is in part attributable to the absence of a suitable thermal comfort model. In consequence, it is important to pursue better prediction of thermal comfort in office buildings and it is worthwhile doing so using the multi-domain approach. This study looks at existing thermal comfort models to identify potential variables from multiple domains that may aid in better explaining and prediciting thermal comfort in offices.

1.2 thermal comfort variables

Existing multi-domain studies identify several variables that are of interest to thermal comfort modelling. A list of main effects and interaction effects that are supported or rejected by existing research on multi-domain thermal comfort in offices is composed [6]. Based on these findings, a series of hypotheses on the direct effects M_i and the indirect effects I_i on thermal (dis)comfort are constructed. For example, existing studies suggest that sound exerts a direct effect on thermal discomfort. Existing research also suggests that the effect of temperature dominates other physical aspects. Several studies show that individual personality traits, such as extraversion, may have both a direct and indirect influence on thermal discomfort. The current study uses gregariousness and assertiveness to represent extraversion. Occupant assertiveness is a facet of extraversion that reflects a person's willingness to take charge, while occupant gregariousness is a facet of extraversion that reflects a person's disposition to be sociable.

The focus of the study is on thermal discomfort during the cooling season and the hypotheses are:

$M1$: Air temperature exerts a positive, exponential, effect on thermal discomfort.

$M2$: Sound pressure exerts a positive effect on thermal discomfort.

$M3$: Occupant gregariousness exerts a negative effect on thermal discomfort.

$I1$: Air temperature exerts a negative effect on the interaction effect between sound pressure level and illuminance on thermal discomfort.

$I2$: Occupant assertiveness exerts a positive effect on the effect of air temperature on thermal discomfort.

$I3$: Occupancy count exerts a positive effect on the effect of occupant gregariousness on thermal discomfort.

The aforementioned hypotheses are tested via an explanatory model, using field measurement data. The results are used to train a model that aims to predict whether office employees are experiencing thermal comfort or discomfort. The articulation of the modelling outcome is unprecedented in current literature, covering three physical variables (air temperature, illuminance and sound pressure level), one contextual variable (occupancy count), two personal variables (occupant assertiveness and gregariousness) and one social variable (gender), in the interest of testing whether such a multi-domain approach can aid in a better understanding or prediction of thermal (dis)comfort in offices.

2. Research methods

The data was collected prior to this study, in two office buildings in the Netherlands. The cross-sectional campaign was conducted during the years 2015-2018. The applied measurement protocol is described in a publication by Brink and Mobach [7]. The data points used in this study are limited to the warmer months of June and July 2016. 623 office employees participated in the measurements. A summary of the demographics is available in Appendix A. The final sample size is equal to 522, of which 493 participants have a sedentary occupation. Their metabolic rate is assumed to be constant. The clothing insulation value is calculated according to the ASHRAE-55-2017 standard [1]. Adaptive opportunities such as clothing ($N = 352$), temperature control ($N = 125$) and operable windows ($N = 515$) are available to the participants. However, perceived control and adaptive behaviour are not recorded and are thus excluded from the study. The measurement procedure consists of objective and subjective measurements. Most objective measurements, such as physical and contextual observations, are performed by the experiment leader. Subjective data concerning the social and personal domains, as well as occupants' thermal perception, is collected via an online questionnaire. The items are available in appendix B.

2.1 explanatory modelling

Explanatory modelling is performed via structural equation modelling (SEM); a covariance-based technique that enables the inclusion of observable and unobservable variables. The latter is important, since the model includes personality traits, which are unobservable constructs, modelled using a set of questionnaire items. An additional advantage of SEM is the graphical aspect that allows the user to visualize relationships between the variables. This is done using standard LISREL matrix notation [8]. The computation is performed via the lavaan package [9].

Tab. 1 provides an overview of the variables used, along with their notation. Variables T_{in}, SPL, E and N_{occ} are continuous. Variables $a_1 - a_2$ and $g_1 - g_4$ are ordinal. All variables are normalized using min-max feature scaling. To account for multivariate non-normality, robust diagonally weighted least squares (DWLS) estimation, known as weighted least square mean and variance adjusted estimation (WLSMV) in lavaan, is used to compute the parameter estimates, robust standard errors and fit indices. Several fit indices are used to evaluate DWLS estimation for ordinal data, namely the Root Mean Square Error of Approximation (RMSEA), the Bentler Comparative Fit Index (CFI) and the Standardized Root Mean Square Residual (SRMSR).

2.2 predictive modelling

The predictive model takes the form of a binary classifier that predicts whether a participant is experiencing thermal comfort or discomfort. The variables included in the model are listed in **Tab.2**. Two linear and two non-linear classification algorithms are selected and trained using the scikitlearn Python library [10]. P_0 is used for linear algorithms, while P_1 is used for non-linear algorithms, as the latter are expected to capture non-linear relationships. The linear algorithms are logistic regression (LR) and linear support-vector machine (L-SVM), while the non-linear algorithms are random forest ensemble (RF) and non-linear support-vector machine that uses the radial basis function kernel (RBF-SVM).

The four models are trained using 231 observations and validated using 77 observations. A search space is proposed for each model, with the objective to maximize the weighted F_1-score, while also tuning the models' respective regularization coefficients. The search is performed on the training set, with 5-fold cross validation yielding the average weighted F_1-score to be maximized. It is performed using the popular Tree of Parzen Estimators (TPE) algorithm which suggests future hyper-parameter choices based on the previous results [11]. 3,000 hyper-

Tab. 1 – Direct and indirect effects included in the SEM model.

Effect	Domain	Symbol	SEM	Variable	Range [unit]
Direct	Physical	$exp^{T_{in}}$	x_8	Air temperature	20 – 26 [^oC]
		SPL	x_9	Sound pressure level	40 – 70 [$dB(A)$]
		E		Illuminance[a]	0 – 2,000 [lx]
	Personal	g_1	x_1	Gregariousness	
		g_2	x_2	Gregariousness	
		g_3	x_3	Gregariousness	
		h_1	y_1	General body discomfort	
		h_2	y_2	Lower body discomfort	
		h_3	y_3	Upper body discomfort	
Indirect	Physical	$SPL \cdot E \cdot T_{in}$	x_{10}	Sound, illuminance and temperature	
	Physical and personal	$T_{in} \cdot a_1$	x_4	Temperature and assertiveness	
		$T_{in} \cdot a_2$	x_5	Temperature and assertiveness	
	Contextual and personal	$N_{occ} \cdot g_1$	x_6	Occupancy count and gregariousness	$N_{occ} < 20$
		$N_{occ} \cdot g_4$	x_7	Occupancy count and gregariousness	$N_{occ} < 20$

[a] The direct effect of illuminance is excluded but illuminance is used to compute $SPL \cdot E \cdot T_{in}$.

parameter choices are evaluated for each model and the highest score is selected. During the testing phase, the four models are retrained on 308 observations, comprising the training and validation sets, and are then tested on the remaining 77 observations. Common classification metrics such as the F_1-score, accuracy (ACC) and the area under the ROC curve (AUC) are used. The aforementioned metrics are based on elements of the confusion matrix; true-positive predictions (TP), true-negative predictions (TN), false-positive predictions (FP) and false-negative predictions (FN). The higher the number of true predictions, the higher the scores.

Tab. 2 – Variables used for prediction.

Variable	Symbol
Indoor temperature exponent	P_0
Indoor temperature	P_1
Sound pressure level	P_2
Sound × illuminance × temperature	P_3
Gregariousness × occupancy count	P_4
Gender	P_5

3. Results

3.1 structural equation modelling

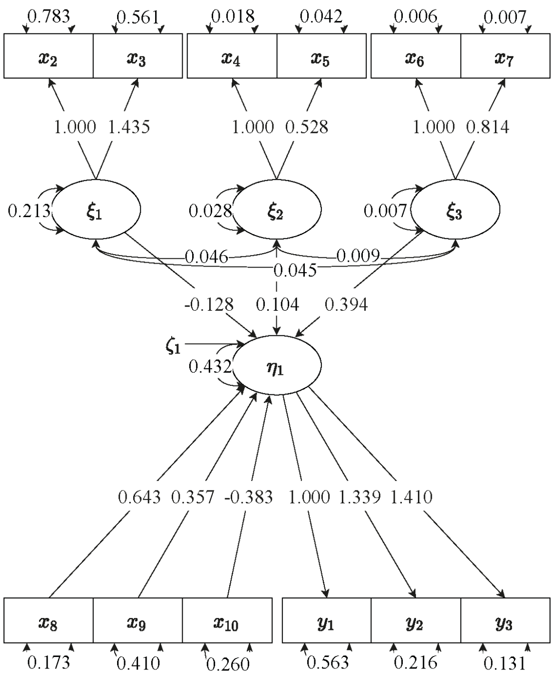

Fig. 2 - Graphical representation of model estimation.

The outcome of the explanatory modelling phase is a SEM model. **Fig. 2** shows the parameter estimates, variance/covariance estimates and factor loadings for the explanatory model. The model fit is summarized in **Tab. 3**. According to the fit indices, the model constitutes an acceptable fit, indicating that the model is capable of explaining thermal comfort in relation to the data.

Tab. 3 – Fit indices used to evaluate the SEM model.

Fit Index	Value
CFI	0.956[a]
$RMSEA$	0.075[b]
CI_{low}	0.064[b]
CI_{high}	0.087[a]
$SRMR$	0.037[a]

[a] Good.
[b] Acceptable.

The parameter estimates are shown in **Tab. 4.** The exponent of air temperature x_8 is expected to have a positive effect on thermal discomfort η_1. According to the results, the effect of x_8 on η_1 is positive (see Fig. 2) and significant at 99.9% confidence ($z>3.09$, $p<0.001$). Sound pressure level x_9 is expected to exert a positive effect on η_1. The main effect of sound pressure level x_9 is found to be positive and significant at approximately 98% confidence ($z>2.33$, $p<0.02$).

Tab. 4 – Parameter estimates for the thermal comfort variables included in the SEM model.

	Estimate	SE	Z	P(<|z|)
x_8	0.643	0.203	3.177	0.001[a]
x_9	0.357	0.151	2.368	0.018[b]
x_{10}	-0.383	0.196	-1.951	0.051[c]
ξ_1	-0.128	0.174	-0.736	0.462
ξ_2	0.104	0.382	0.272	0.785
ξ_3	0.394	0.198	1.988	0.047[c]

[a] CI – 99.9%.
[b] CI – 98%.
[c] CI – 95%.

The interaction between indoor temperature, sound pressure level and illuminance x_{10} is expected to exert a negative effect on η_1, such that an increase in indoor temperature will result in a decreased audio-visual influence. The parameter estimate for the three-way interaction x_{10} is found to be negative and significant at 95% confidence ($z>1.96$, $p<0.05$). Gregariousness x_1 is expected to exert a negative effect on η_1. The effect of x_1 on η_1 is found to be negative but it is not found to be significant. The interaction between assertiveness and indoor temperature x_2 is expected to be positive, to the extent that an increase in temperature will result in an increased influence of assertiveness on η_1. The two-way interaction x_2 is found to be positive but it is not found to be significant. The interaction between gregariousness and occupancy count x_3 is expected to be positive, such that an increase in occupancy count will result in an increased influence of gregariousness on η_1. The two-way interaction x_3 is found to be significant at approximately 95% confidence ($z>1.96$, $p<0.05$). As a result, hypotheses $M1$, $M2$, $I1$ and $I3$ are not rejected.

3.2 binary classification

The outcome of the predictive modelling phase are four models; LR, L-SVM, RF and RBF-SVM. LR is fitted as shown in equation (1). The polarity of the parameter estimates is consistent with hypotheses $M1$, $M2$, $I1$ and $I3$, suggesting the model learned a similar pattern to the one captured using SEM.

$$P(Y=1|X) = \frac{exp(-0.27+0.29X_0+0.30X_2-0.13X_3+0.17X_4+0.23X_5)}{1+exp(-0.27+0.29X_0+0.30X_2-0.13X_3+0.17X_4+0.23X_5)} \quad (1)$$

Fig. 3 shows the confusion matrix, obtained by running LR, L-SVM, RF and RBF-SVM on the test set. The number of true predictions for the four models ranges between 42 and 46. The large number of false negative predictions, ranging between 19 and 25, suggests that all four models have difficulty predicting thermal discomfort.

Actual value	Predicted value: 1	Predicted value: 0
Discomfort: 1	TP LR 22 L-SVM 28 RF 23 RBF-SVM 25	FN LR 25 L-SVM 19 RF 24 RBF-SVM 22
Comfort: 0	FP LR 9 L-SVM 12 RF 11 RBF-SVM 11	TN LR 21 L-SVM 18 RF 19 RBF-SVM 19

Fig. 3 – Confusion matrix for the test set.

Tab. 5– Performance metrics (validation and testing).

Model	Set	*AUC*	*ACC*	F_1
LR	Valid	0.58	0.56	0.53
	Test	0.68	0.56	0.56
L-SVM	Valid	0.58	0.61	0.61
	Test	0.67	0.55	0.55
RF	Valid	0.62	0.60	0.60
	Test	0.64	0.58	0.59
RBF-SVM	Valid	0.57	0.52	0.48
	Test	0.66	0.57	0.58

The performance metrics for the validation and testing phases are reported in **Tab. 5**. The difference in performance across the models is very slight and all four models yield similar scores across all three metrics. While L-SVM and RF show better *ACC* and weighted F_1 on the validation set, they no longer outperform the other models on the test set. The increase in ACC during the testing phase for all four predictive models could be attributed to random variation between data splits. The predictive performance of the models is just above random guessing (= 0.50) and is not sufficient for predicting thermal (dis)comfort.

4. Explaining thermal comfort

The interpretation of the SEM model addresses the hypotheses $M1-M3$ and $I1-I3$. The model estimates do not reject $M1, M2$, $I2$ and $I3$, leading to several implications that may be of interest to the understanding of thermal comfort in offices:

- During the cooling season, an increase in indoor temperature results in an exponential increase in thermal discomfort.
- An increase in sound pressure level results in an increase in thermal discomfort.
- An increase in air temperature decreases the effect that the interaction between sound pressure level and illuminance has on thermal discomfort, resulting in a negative three-way interaction.
- An increase in occupancy count increases the effect of occupant gregariousness on thermal discomfort, resulting in a positive two-way interaction.

The fit indices and the polarity of the parameter estimates support the notion that the model may be used to explain thermal comfort. However, the existence of a near-equivalent model is likely. The reliability of the subjective data, particularly assertiveness and gregariousness, is questionable. A better fit may be achieved via the use of a more extensive and well-known scale, such as the IPIP-NEO-120 [12].

5. Predicting thermal comfort

The SEM model suggests that P_0-P_5 significantly affect thermal comfort in offices. Yet, the four predictive models are not capable of adequately predicting thermal (dis)comfort. Looking at all four outcomes, the quality of the data may have introduced noise, masking the patterns necessary for making reliable predictions. However, real-world data is noisy and constitutes a pitfall for even the most prevalent models. A predictive model can be expected to perform even worse in practice than it does on the mother data set. The results show that thermal comfort is a complex, multi-domain construct that is difficult to predict. However, the performance of the four predictive models does not cast a definitive shadow over the prospect of accurate prediction. Predictive models that include a larger number of thermal comfort variables and higher quality subjective measurements may yield better predictions. Moreover, other, more advanced modelling techniques, such as stochastic modelling, may be better suited for thermal comfort prediction.

6. Conclusion

This study applies the multi-domain approach to thermal-comfort modelling. An explanatory model is constructed using SEM. The specified model examines the influence of indoor temperature, illuminance, sound pressure level, occupancy count, gregariousness and assertiveness on thermal discomfort. The SEM model is unique, as it is the first explanatory model, derived from field measurements, to include multiple physical and personal variables, while also including contextual variables. The following conclusions are derived from the explanatory model:

- Thermal discomfort increases at higher indoor temperatures and higher sound pressure levels, suggesting that both should be optimized and maintained during the design and operation phase.
- Uncomfortably high indoor temperatures decrease the effect that sound pressure level and illuminance otherwise have in a comfortable thermal environment. This highlights the importance of designing for optimal temperature conditions and constitutes a basis for the use of personalized heating and cooling strategies to optimize individual temperature conditions.
- Gregarious individuals may be more thermally comfortable than non-gregarious individuals when there are many occupants in the room. While it is not feasible to obtain information on personality traits during the design phase, designers are encouraged to account for inter-individual differences by providing flexible working conditions.

Four predictive models LR, L-SVM, RF and RBF-SVM are trained using significant variables P_0-P_5. The models examine the predictive potential of the explanatory model. All models struggle to predict thermal (dis)comfort, despite the inclusion of significant thermal comfort variables. The results bring to light several conclusions:

- Significant thermal comfort influences are not always adequate predictors thereof.
- Researchers are advised to precede future thermal comfort studies with explanatory modelling, to facilitate the creation of predictive models that contain a large variety of physical, contextual, social and non-social variables.
- Combined use of explanatory and predictive modelling is necessary, to test whether variables considered in thermal comfort research hold theoretical relevance, predictive potential, both or, perhaps, neither.

This study is part of a broader research effort to achieve better prediction of thermal comfort in offices, which is an essential step in the building design process. The results formulate a basis for further research on the influence of indoor climate, occupancy and personality traits on thermal comfort in offices, as well as the interaction between the different influences. Moreover, the findings have direct implications for the engineering sector, as they suggest that influences such as sound pressure level, occupancy and personality traits, should be considered when designing for optimal thermal conditions.

6.1 limitations

This research is subject to several limitations, the mitigation of which is encouraged in the future. Firstly, prominent variables such as correlated colour temperature and air velocity are not included in the study. Similarly, variables such as age, relative humidity, clothing insulation and metabolic rate are excluded due to insufficient variability in the measured data. Secondly, extreme indoor conditions are not observed during field measurements. In addition, the measurements are limited to summer conditions in the context of the Netherlands and are not representative of cooler conditions or other climate regions. Due to this limitation, the relationship between temperature and thermal discomfort is assumed to be exponential. Future studies are encouraged to include cold sensation data and thereby model a parabolic relationship between temperature and thermal discomfort, where thermal discomfort increases at lower and higher temperatures both. Thirdly, the internal consistency of the personal variables is poor and they are not sufficiently representative of the Big Five personality traits. Lastly, the quality of the predictive models may be improved via the use of advanced hyper-parameter tuning, a larger variety of machine learning algorithms and more advanced modelling methods.

7. Acknowledgement

The data is provided by the research group of Mark Mobach at the Hanze University of Applied Sciences. The authors acknowledge the contribution of Yasin Toparlar, Deerns Groep B.V.

8. Data access statement

The dataset generated and analysed during the current study is available in the 4TU repository [13].

Appendix A

Tab. A1 – Demographics for offices 1 and 2.

Gender		Office 1		Office 2	
		$\mu \pm \sigma$	N	$\mu \pm \sigma$	N
Male			154		88
	Age	43 ± 10		47 ± 8	
	Clo	0.5 ± 0.1		0.4 ± 0.1	
Female			170		112
	Age	43 ± 10		45 ± 8	
	Clo	0.5 ± 0.1		0.5 ± 0.2	

Appendix B

Tab. B1 - Items, item scales and reliability concerning thermal comfort constructs.

Construct	Item	Likert scale	Cronbach's alpha α
Thermal discomfort			0.83
General discomfort (heat)	It is too hot in here now.	5-point	0.87
Lower body discomfort	I have warm feet.	5-point	0.71
Upper body discomfort	I have warm hands.	5-point	0.69

Tab. B2 - Items, item scales and reliability concerning personality facets.

Construct	Item	Likert scale	Cronbach's alpha α
Gregariousness			0.55
	I prefer to work in a completely open space with several people.	5-point	0.43
	I prefer to work alone in a room. (excluded)	5-point (R)	0.40
	I love working with others. (excluded)	5-point	0.47
	I involve my colleagues in carrying out my work.	5-point	0.57
Assertiveness			0.46
	I can always communicate in an open way.	5-point	
	I adjust my job to the work of my colleagues.	5-point	

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