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DOI

[10.34641/clima.2022.219](https://doi.org/10.34641/clima.2022.219)

Publication date

2022

Document Version

Final published version

Published in

CLIMA 2022 - 14th REHVA HVAC World Congress

Citation (APA)

Ghering, V., van den Brom, P. I., Itard, L. C. M., & Schipper, H. R. (2022). Simulated thermal comfort in renovated houses with low temperature heating. In *CLIMA 2022 - 14th REHVA HVAC World Congress: Eye on 2030, Towards digitalized, healthy, circular and energy efficient HVAC* Article 1422 TU Delft OPEN Publishing. <https://doi.org/10.34641/clima.2022.219>

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Simulated thermal comfort in renovated houses with low temperature heating

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Abstract. Low Temperature Heating (LTH) of buildings is a key feature when switching to renewable energy. Even when the capacity of LTH is high enough, LTH may adversely affect indoor thermal comfort in case buildings are not suitably insulated. This paper goes deeper into methodological issues when conducting a thermal comfort assessment. Thermal comfort is either quantified by Fanger's Predicted Mean Vote (PMV) or ranked in building comfort classes in the adaptive model. In both cases, one of the main parameters influencing comfort is the Mean Radiant Temperature (MRT). This study addresses issues with common MRT and PMV calculations in energy simulation software. The case study is TRNSYS 17. Several MRT and PMV calculation methods are compared, showing possible draw-backs and deviations from comfort standards NEN-EN ISO 7726 and 7730. For instance, in the standard heating settings in TRNBuild only the total heating capacity is specified. The radiative part is then distributed area-weighted over opaque surfaces. A more detailed option in TRNBuild is to specify the locations of radiative gains as points. In both cases, the MRT at a comfort sphere is calculated with Gebhardt-factors instead of view-factors. The standard settings may be considered too simplified for detailed comfort studies whereas the detailed model shows deviations from comfort standards NEN-EN ISO 7726 and 7730. Therefore, two additions to these models are proposed to increase accuracy. One addition is an ordinary detailed model with radiative gains as point sources in order to retrieve all surface temperatures during a desired period of time. In the second addition walls with radiators are split-up and planes are added at the locations of radiators to generate a view-factor matrix. This can be done in TRNBuild, but also in other view-factor calculation software. From model 1 all surface temperatures are retrieved. Combined with the view-factors from model 2, the MRT can be calculated.

Keywords. Thermal Comfort, low temperature heating, dwellings, energy transition

DOI: <https://doi.org/10.34641/clima.2022.219>

1. Introduction

In 2021, around 75% of the building stock in the European Union was considered to be energy inefficient, whilst 90% of these buildings are expected to still be standing in 2050 [1]. Energy labels in The Netherlands further substantiate the claim that buildings are still performing relatively poor in terms of their energy use, with an average label of C for all residences in 2019. Especially older dwellings, with construction years <1980, have poor energy labels of D or lower. Yet the vast majority of the residential building stock consists of these older dwellings [2].

In dwellings, energy is used for several purposes. The main categories that can be distinguished for energy use in The Netherlands are: space heating, cooking, hot tap water, lighting and 'other'. The largest share of energy is used for space heating but in recent years also cooling has become an increasing factor of the total energy demand. The main source of energy in The Netherlands, but also in the UK, is natural gas. The total natural gas consumption has been decreasing between 1995 and 2015 but has since then stagnated [3], whilst a further reduction (if not complete elimination) is strongly desired.

In order to pull these older, energy inefficient

dwelling through the energy transition, a mix of interventions can be carried out. Whilst a demolish and rebuild option of the old building stock is an option, renovations often require less resources and time and impose less intrusion on residents and are therefore often preferred where possible [4].

An effective way to reduce the primary energy demand from finite resources for space heating, is adding insulation (reducing the heat loss of the building) combined with the use of low temperature heating (LTH) opposed to high temperature heating (HTH). In order to effectively and comfortably use LTH and further reduce energy demand, a sufficient level of insulation should be present. In older dwellings, this is often not the case, leading to uncomfortable situations due to a capacity deficit of LTH systems.

This paper aims to evaluate the use of TRNSYS 17 for a comfort assessment. First a literature review on LTH, Thermal comfort and TRNSYS will be presented. Then the results will be provided followed by a discussion and conclusion.

2. Literature

In this chapter the results of a literature review on LTH, thermal comfort and TRNSYS 17 will be presented in order to further elaborate the reasons for this paper.

2.1 Low Temperature Heating

In colder climates, like The Netherlands, space heating is one of the main energy consuming factors of buildings [3]. Increasing insulation values of the building envelope reduces the amount of heat loss to the environment and thus the amount of energy required for space heating. It also enables temperatures of the heating system as a whole to be lowered. This further reduces the required primary energy demand and enables more efficient and renewable heat energy sources such as heatpumps, geothermals etc..

The energy for space heating is often supplied in the form of warm water. The heat is transferred to the room via a delivery system such as radiators or underfloor heating. The energy the water can deliver to the delivery system can be determined with [5]:

$$Q = \dot{m} * C_p * (T_h - T_c) \quad (1)$$

Where: Q = capacity (W), \dot{m} = mass flow rate of the water, C_p = specific heat capacity of water (J/kg °C), T_h = inlet water temperature (°K), T_c = outlet water temperature (°K)

From this equation it becomes clear the capacity of the radiator is not dependent on the temperature of the water, but the temperature difference of hot inflowing and cold outflowing water. The heat from the radiator is transferred to the room via convection

and radiation. For convection, the heat transfer equation is [6]:

$$Q_{conv} = h * A * (T_{rad} - T_{air}) \quad (2)$$

Where: Q_{conv} = capacity of the convective part (W), h = convective heat coefficient (W/m² °C), A = surface area of radiator (m²), T_{rad} = temperature of the radiator (°K), T_{air} = air temperature (°K)

For the radiative part, heat transfer happens through [6]:

$$Q_{rad} = \varepsilon * \sigma * A * T_{rad}^4 \quad (3)$$

Where: Q_{rad} = capacity of the radiative part (W), ε = emissivity (-), σ = Stefan Boltzmann constant (5.67*10⁻⁸ W/m² °K), A = surface area of radiator (m²), T_{rad} = temperature of the radiator (°K)

From these equations, it can be seen that the heat delivery of the radiator is dependent on the surface area of this radiator and the temperature of the radiator. In this instance, LTH will reduce the capacity compared to HTH if this is not mitigated through the surface area or the convective coefficient of the installed radiator. This means that in most cases, the heating delivery system will also need to be adjusted when changing to LTH.

2.2 Thermal Comfort

Thermal Comfort is defined as

"the condition of mind the expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [7]

In The Netherlands, thermal comfort is formulated in NEN-EN ISO 7730 [8]. This standard is based on Fanger's Predicted Mean Vote (PMV). This comfort theory is based on the following energy balance:

$$M = P_c + P_{zv} + P_g + P_{ma} + P_d + P_s + P_{av} + P_{al} \quad (4)$$

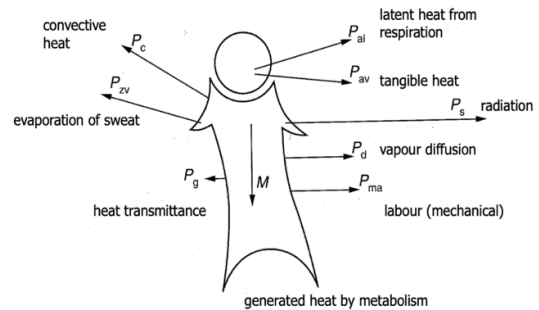


Fig. 1 – PMV principle [9]

Calculate the PMV using Equations (1) to (4):

$$PMV = [0,303 \cdot \exp(-0,036 \cdot M) + 0,028] \cdot \left\{ \begin{aligned} &(M - W) - 3,05 \cdot 10^{-3} \cdot [5,733 - 6,99 \cdot (M - W) - p_a] - 0,42 \cdot [(M - W) - 58,15] \\ &- 1,7 \cdot 10^{-5} \cdot M \cdot (5,867 - p_a) - 0,0014 \cdot M \cdot (34 - t_a) \\ &- 3,96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{aligned} \right\}$$

$$t_{cl} = 35,7 - 0,028 \cdot (M - W) - J_{cl} \cdot \left\{ 3,96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \right\}$$

$$h_c = \begin{cases} 2,38 \cdot |t_{cl} - t_a|^{0,25} & \text{for } 2,38 \cdot |t_{cl} - t_a|^{0,25} > 12,1 \cdot \sqrt{v_{ar}} \\ 12,1 \cdot \sqrt{v_{ar}} & \text{for } 2,38 \cdot |t_{cl} - t_a|^{0,25} < 12,1 \cdot \sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1,00 + 1,290 I_{cl} & \text{for } I_{cl} \leq 0,078 \text{ m}^2 \cdot \text{K/W} \\ 1,05 + 0,645 I_{cl} & \text{for } I_{cl} > 0,078 \text{ m}^2 \cdot \text{K/W} \end{cases}$$

where

- M is the metabolic rate, in watts per square metre (W/m^2);
- W is the effective mechanical power, in watts per square metre (W/m^2);
- I_{cl} is the clothing insulation, in square metres kelvin per watt ($m^2 \cdot K/W$);
- f_{cl} is the clothing surface area factor;
- t_a is the air temperature, in degrees Celsius ($^{\circ}C$);
- \bar{t}_r is the mean radiant temperature, in degrees Celsius ($^{\circ}C$);
- v_{ar} is the relative air velocity, in metres per second (m/s);
- p_a is the water vapour partial pressure, in pascals (Pa);
- h_c is the convective heat transfer coefficient, in watts per square metre kelvin [$W/(m^2 \cdot K)$];
- t_{cl} is the clothing surface temperature, in degrees Celsius ($^{\circ}C$).

NOTE 1 metabolic unit = 1 met = 58,2 W/m^2 ; 1 clothing unit = 1 clo = 0,155 $m^2 \cdot K/W$.

Fanger's theory states that if the incoming energy from the metabolic rate is equal to the sum of the outgoing energy fluxes, a comfortable situation is reached resulting in a PMV of 0. If the outgoing energy is greater than the incoming energy, a sensation of coldness will occur, resulting in a negative PMV. A positive PMV is achieved when the sum of the incoming energy is larger than the outgoing energy and is linked to a sensations of being warm. The PMV results are scaled between -3 (cold) to +3 (hot).

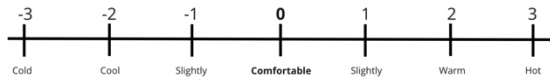


Fig. 2 – PMV scale

In order to provide an insight into how people experience the PMV score, the Percentage of People Dissatisfied (PPD) was developed. This PPD is directly linked to the PMV. At a PMV of 0, the PPD shows that still 5% of people will be uncomfortable. A building performs well if 10 % of people are dissatisfied, resulting in a PMV of 0.5. The PMV should not exceed 0.7 resulting in a PPD of 15 %.

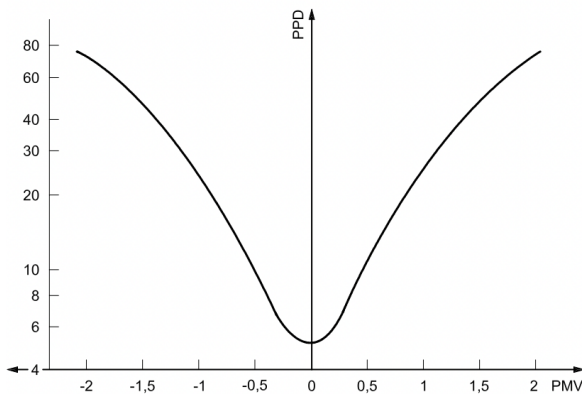


Fig. 3 – PPD link to PMV [9]

A second way to assess thermal comfort is the adaptive thermal comfort model. This model assumes that people can take actions to mitigate thermal discomfort. These actions involve, among others, changing attire, opening windows or changing the activity they partake in.

The adaptive model is based on the operative temperature, which is formulated based on the mean radiant temperature (MRT) and the indoor air temperature. This operative temperature is plotted against the running mean external temperature which takes the last 7 days into account. This is done to discount for weather deviations per day [9].

The plotted points are evaluated against 3 bandwidths. If all points fall within the narrowest bandwidth, a building is qualified as a class A(B) building and is deemed comfortable.

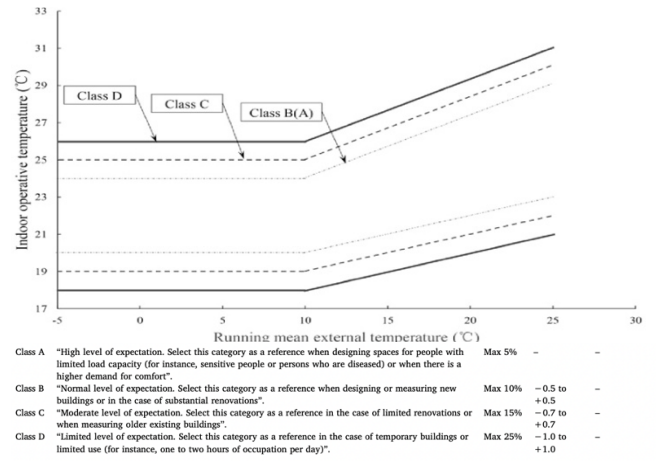


Fig. 4 – Adaptive comfort [10]

Whether thermal comfort is determined via the PMV or adaptive model, the Mean Radiant Temperature of the surfaces in a thermal zone are of significant impact on the comfort sensation. This MRT is calculated not only based on the temperatures of the planes, but also their relative orientation to the comfort sensor. This sensor is usually a sphere, which can accurately resemble a seated person.

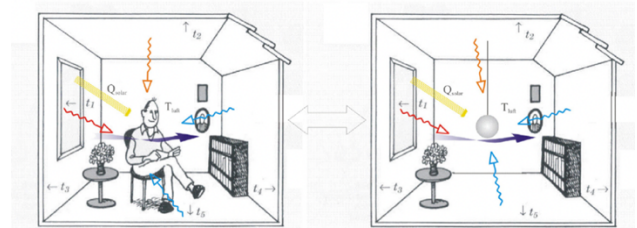


Fig. 5– MRT principle [11]

In The Netherlands NEN-EN ISO 7726 [12] prescribes how the MRT should be calculated. The most elaborate but also most thorough method is via view factors. The MRT can then be calculated through:

$$MRT = \left(\sum_{i=0}^n T_i^4 \cdot F_{p \rightarrow i} \right)^{\frac{1}{4}} \quad (5)$$

Here T_i is the surface temperature of surface i and $F_{p \rightarrow i}$ is the view factor from the comfort sphere to surface i . The view factors are dependent on orientation and surface areas of the individual planes.

2.3 TRNSYS 17

TRaNsient SYStems 17 (TRNSYS 17) is a validated and widely used program to simulate energy flows in a variety of systems through a set timeframe. Originally the program focused on solar energy systems but over years it has been elaborated to carry out a variety of simulations [13]. One addition is the option to simulate a full dwelling. A geometry can be set up in Sketchup 2014 with the plugin TRNSYS3D. TRNSYS3D can read the geometry and assign boundaries to planes. These boundaries can either be another thermal zone, ground or the outdoors. The geometry can be inputted into TRNBuild where properties can be added to the individual planes, ventilation and infiltration regimes can be assigned to thermal zones and a heating system can be implemented.

All this information is linked to the TRNSYS simulation studio in the Type 56 component [14]. Individual components can be linked to form a closed energy loop. The simulation studio is also where the time settings can be adjusted. Examples of time settings are the desired time period the simulation runs, the time steps and tolerances for the solver. In addition, weather and ground temperature data can be loaded into the project here.

The components are all open source. This ensures a 'black-box' idea can be avoided. The comfort calculation in TRNSYS 17 is however carried out in the 'Type 56: multi-zone building' component. This Type is more elaborate than the other Types and has its own interface in the form of TRNBuild. The functionality of this Type is explained in TRNSYS manual Volume 5. Here it is stated that the PMV and PPD are calculated via NEN-EN ISO 7730. The MRT is however not based on view factors but on Gebhardt factors [14]. These factors take view factors into account but also add a component that states the emissivity of the surrounding surfaces.

$$T_{MR} = \left(\sum_{i=0}^n T_i^4 * G_{S,i}^{LW} \right)^{\frac{1}{4}} \quad (6)$$

$$G_{ir} = (I - F\rho_{ir})^{-1} F \varepsilon_{ir} \quad (7)$$

Where:

- G_{ir} The Gebhardt factor matrix
- I Identity matrix
- F View Factor matrix
- ρ_{ir} Hemispherical Longwave reflectivity
- ε emissivity matrix

Radiators cannot be implemented as planes in TRNSYS 17. The first and most simplified way to implement radiators is to add a certain maximum heating capacity to a thermal zone where TRNSYS

will assign the radiative part of the heating system area-weighted to the individual planes. If the locations of the radiators are to be specified, this can be done through infinitesimal points. A point source view factor matrix is then created with the use of solid angles.

Outputs of the simulations can either be directly displayed in graphs and charts or stored in CSV files.

3. Method

In order to assess the functioning of the comfort simulations in TRNSYS 17, an existing terraced dwelling in The Netherlands was modelled. One of reasons for choosing this dwelling was the availability of measured data. In the months of November and December, measurements of air and surface temperatures were taken. The measured data was used to calibrate the model in TRNSYS. The air temperatures were measured at the green dots in figure 6 whilst surface temperatures were measured at the red dots. Three comfort sensors were modelled at the blue dots.



Fig. 6– Floorplans case study dwelling

Radiators are modelled as point sources in the heart of the existing radiators. Their respective capacities are derived from the data based on their size and type. View factors are calculated through a work-around.

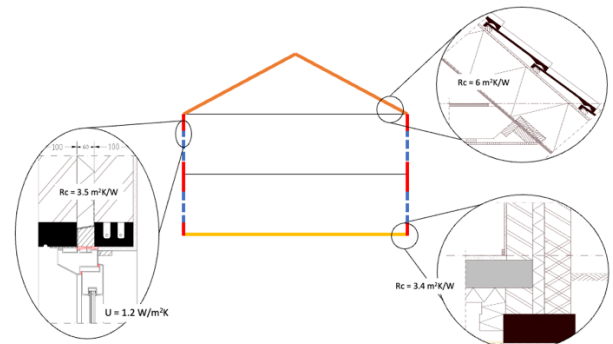


Fig. 7– Thermal insulation studied dwelling

The properties of the shell of the dwelling were derived from a previous survey. The heating system used for the calibration closely resembles a common HTH system in The Netherlands where a central heating unit is connected to a set of radiators. A central pump is the driving force to ensure waterflow and a thermostat regulates the setpoints.

During heating season, the setpoint was set at 18,5 °C

and raised to 20 °C between 15:00 and 22:00 hours. This temperature profile was chosen to match the settings the residents used at the time of measurement. For the heat recovering ventilation unit, flow rates were matched to the Bouwbesluit 2012. Infiltration was set to match class 2 'Good' standards for airtightness of building. The weather input data was linked to a weather file from the KNMI from the year 2020. Timesteps were set to 0.01 hour (6 seconds).

The metabolic rate was determined at 1.2, the clothing factor at 1, external work at 0 and the air velocity at 0.1. The ventilation

The outcomes of the TRNSYS 17 model were then compared to the measured data. Unknown properties of the heating system were adjusted (within realistic boundaries) until a close match was found between the measured and modelled data.

4. Results

In this chapter the results will be presented. First the results of the calibration process will be given. Then the comfort assessment of TRNSYS 17 will be evaluated against 4 other calculation tools.

Figure 8 shows the measured air temperatures in the living room and the modelled temperatures. Figure 9 shows the measured and modelled surface temperatures as measures. Except for the surface temperature of the façade, the measured and modelled data are deemed to be a close enough resemblance to perform a comfort comparison. Deviations most likely occur due to thermostat settings by the residents. This goes especially for the period between 21-11-2020 and 23-11-2020 where the residents were absent and lowered the thermostat in the meantime.

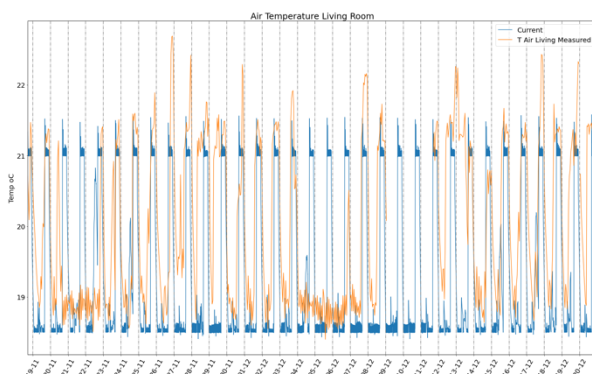


Fig. 8– Measured and modelled air temperatures

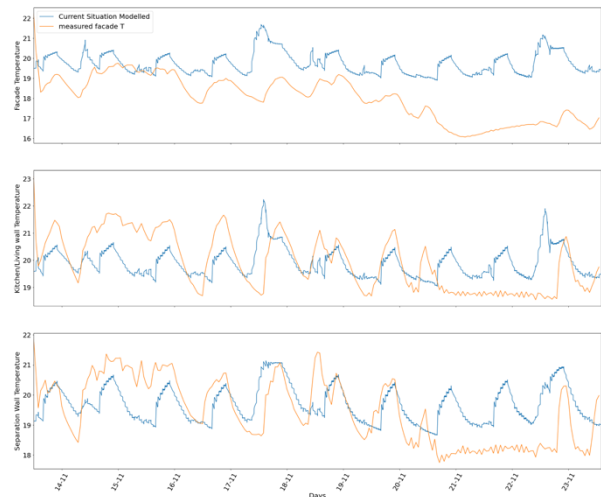


Fig. 9 – Measured and modelled surface temperatures

The surface temperature of the façade is higher in the model than what was measured. A possible explanation is the relatively low thermal conductivity (0.02 W/mK) stated by the manufacturer of the cavity insulation, resulting in an Rc value 3,5 m²K/W. For a cavity of 6 cm a more realistic Rc value after cavity insulation is 1,1 m²K/W. The modelled surface temperature with a façade insulation of 1,1 m²K/W was also carried out and provided a much closer match to the measured data. It was however not deemed proven that the manufacturers claims were faulty since also execution or the state of the cavity could affect the insulation values.

For all time steps, the PMV and individual comfort parameters determined by TRNSYS were loaded into a CSV file. These parameters include the air temperature (°C), mean radiant temperature (°C) (calculated with Gebhardt factors), relative humidity (%) and air speed (m/s).

These parameters were used to compare the PMV results created by TRNSYS 17 to three other tools based on ISO 7730 and one based on EN-16798. The calculation tools included the calcPMVPPD function in the comf R-package [15] an MS Excel tool developed by the Faculty of Mechanical Engineering at the University of Coimbra [16], an Online comfort tool developed by the Centre for the Built Environment at the University of Berkeley [17] and a Python function developed by the author of this paper based on NEN-EN ISO7730. The results of the comfort calculators are presented below.

5. Discussion

The PMV scale of -3 to +3 is a large scale and often not expressed in more than 1 decimal place. A mean difference of 0.028 could also be considered trivial, especially given the accuracy of temperature measurements in general. Often, thermometers have accuracies of 0.25 °C, which will provide different PMV results.

However, since the PMV formulas are so specifically documented and have been around for so long, a difference of 0.028 should not occur at all. An attempt was made to discover a possible reason for the different outcomes. Different solvers for the clothing temperature factor were tried and rounding differences were tested. Solar radiation was also eliminated as a possible reason for overestimation since this is also not taken into account in the PMV calculation of TRNSYS.

It could not be explained why this program calculates a small but persistent difference in the PMV. This makes the program function as a 'black-box', which should always be avoided when executing simulations. Furthermore, the MRT calculation through Gebhardt factors instead of view factors, is a deviation from standards by TRNSYS 17. Additionally, the absence of a function to simulate radiators as planes can create an error in the MRT calculation. Therefore TRNSYS 17 is not deemed a suitable program for extensive thermal comfort assessments of buildings. Although it is a well-documented, validated and commonly used energy simulation program, thermal comfort should be assessed with different packages. Especially in long-term thermal comfort assessment, the difference of 0.03 might make a building pass thermal quality controls, where it actually preforms below standard.

When using TRNSYS 17 for energy simulations in buildings, thermal comfort should be assessed via a work around. A proposed method is to start with 2 TRNSYS 17 models. In one model, the radiators are simulated as points in the centre of the radiators. This model is used to perform the actual energy simulation. From this model, all surface temperatures, air temperatures and relative humidity can be retrieved for each time step.

A second model is then created where radiators are modelled with their actual sizes. If this is done in TRNSYS 17, these planes can only be added inside other surfaces. If these planes were to be added as active layers, this would mean a section of the façade would not be modelled accurately, which would affect the heat loss through this part of the façade and thus the energy demand. This model is only suitable for retrieving the view factors from the comfort sphere to the individual planes (now including the radiators).

With the parameters from model 1 and the view factors from model 2, the MRT can now be calculated

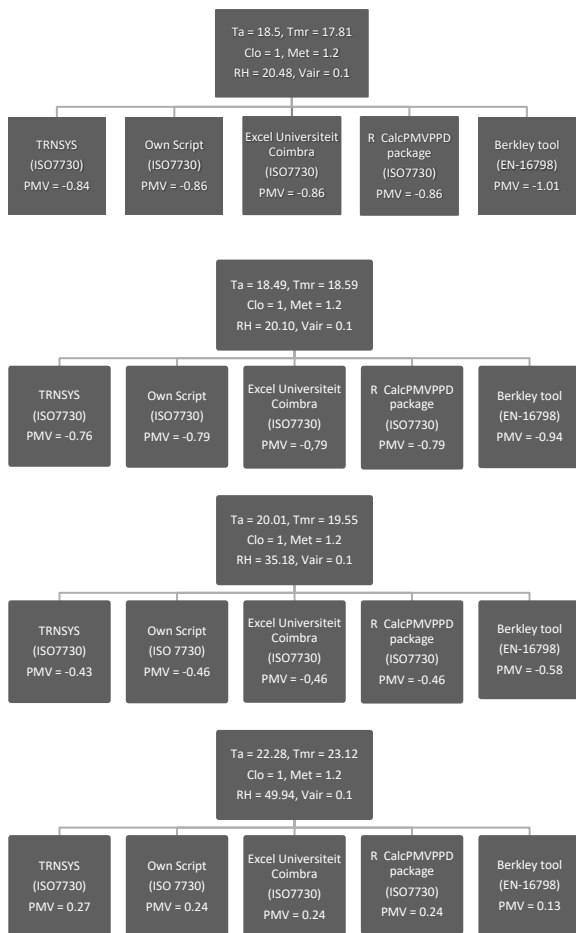


Fig. 10 – PMV calculated for 4 situations with 5 calculators

From these outcomes, it is clear that the PMV calculated by TRNSYS 17 shows an overestimation of the PMV compared to the outcomes of the three other calculators based on NEN-EN ISO7730, with the exact same input. A comparison for the PMV calculated by TRNSYS 17 and the Python function throughout the simulated year is presented in figure 11. The overestimation of the PMV calculated by TRNSYS 17, varies between 0.036 and 0.026 with a mean overestimation of 0.028.

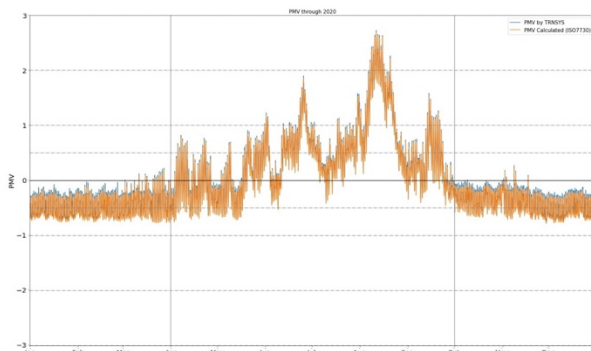


Fig. 11 – PMV calculated for 4 situations with 5 calculators

line with NEN-EN ISO7726 for each time step through for example a Python script or the Comf R-package. Subsequently, the PMV can also be calculated through a Python or R script in line with NEN-EN ISO7730.

A preliminary comfort study, carried out with the proposed work-around in TRNSYS 17, showed that the lowered peak capacity of efficient LTH systems can create uncomfortable situations. With HTH systems, it is not uncommon to have lower temperatures at times of absence or at night and increase the air temperature by over 2 °C for short periods of time. HTH often has an abundance of capacity, enabling systems to reach higher temperatures in a relatively short period of time. LTH systems on the other hand are most efficient if their capacities are closely matched to the required maximum. This also means temperature rises are slower, even when heat losses are minimized (though increased insulation and decreased infiltration rates). Less fluctuation in the temperature regime is therefore advised [18]. Further research could point out what the influence of the LTH heating systems and the used temperature settings is on the indoor thermal comfort and energy use.

Alternative software packages for comfort assessments are not abundant, but present nonetheless. One option is the PMV calculator in IES. Also VABI elements has a pre-built PMV calculator. Another option that was identified was the PMV calculator in the Ladybug/Honeybee extension for Grasshopper. This has an added benefit of enabling parametric engineering. This could be useful when attempting to determine the relative effect of insulation versus infiltration on thermal comfort for example. It should however be mentioned that all three of the named examples should also always be validated before use in a particular simulation.

6. Conclusion

With increased complexity of models and simulations, increased caution is required. When changing to LTH in dwellings in an efficient manner, new heating systems should be installed and often more insulation should be added. In order to find optimized solutions in terms of energy demand reduction with minimal material use, it is important to conduct a thorough and correct comfort assessments. Not only the absolute air temperature is of importance, but also relative humidity, air speed and the mean radiant temperature of the surrounding surfaces play a significant part in the comfort sensation. All these factors are taken into account by the PMV assessment. This increases complexity, but also the possibility to depend on outcomes to be in line with reality.

Although energy simulation software for dwellings should provide the required parameters to also conduct a comfort calculation, this has proven not be

the case for TRNSYS 17. With a terraced dwelling in The Netherlands in 2020 as a case study, TRNSYS 17 overestimated the PMV with a mean of 0.028 throughout the year. Although this deviation might seem small, it should not be there at all. This was proven by the use of 3 other PMV calculation tools based on NEN-EN ISO 7730, which all showed the same results. T

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The datasets generated during and/or analyzed during the current study are not publicly available but are/will be available upon request with the first author of this paper.