Determining occupant's Thermal Comfort and Well-Being towards facilitating energy demand management utilizing a low-cost wearable device

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ABSTRACT

The scope of this work is to provide unobtrusive means to accurately depict the thermal comfort and well-being level of the occupants making them predictable energy wise and allow pertinent personalized feedback notifications or actions towards energy demand management while preserving their corresponding preferences. Specifically, a low-cost wearable wrist device, collects occupant's physiological, motion and indoor environmental condition data using unobtrusive appropriate sensors. Then, accounting the clothing conditions and the mean radiant temperature the occupant's thermal comfort level as well as the indoor air quality is assessed on the scale provided by ANSI/ASHRAE 55-2010 Standard. Thermal comfort and indoor quality levels are critical not only for health matters but also for the productivity of the occupants since it affects humans' efficiency and the mood as well. Being aware of the occupant's thermal comfort level as well as the indoor quality level and the outdoor conditions essential actions can be scheduled regarding the energy demand.

KEYWORDS

Thermal Comfort and Well-being Levels, Energy Demand Management, Low-Cost Wrist Wearable Device, Physiological Parameters, Indoor Environmental Conditions

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1 INTRODUCTION

People spend more than 90% of their time within indoor environments [1], [2]. Suitable thermal comfort plays a significant role in their physical and physiological well-being and productivity [3]. According to the statistics, HVAC systems are responsible for roughly 20% of total energy consumption of a building in developed and developing countries. In the tropics, the energy consumed by an HVAC system may exceed 50% of the total energy consumption of a building. Ensuring a comfortable and healthy indoor environment is of great importance for occupants, as it affects their well-being, productivity, and performance [4].

Thermal sensation (TS) and thermal comfort (TC) relate to the living environments and the life of the occupants. TC expresses the personalized thermal satisfaction of the occupant associated with the thermal environmental conditions. It includes an ideal thermal condition and the corresponding tolerance limits on either side of a thermal scale which the occupant remains comfortable. Well-being status mainly concerns the quality of indoor air in terms of pollutants. Continuously determining occupants' TC and well-being status and adeptly integrating them into the control of the thermal environment of building systems enables optimization of heating, ventilation, and air conditioning (HVAC) energy consumption, thus it is a critical process towards managing energy demand [5]. It is indispensable to enable occupants to depict their own personalized tolerance limits while continuously assessing TC in an automatic manner. Therefore, it is imperative to provide unobtrusive means to accurately determine the personalized thermal comfort / well-being level of the occupants to make them predictable energy wise and allow pertinent personalized feedback for optimal energy demand management while preserving the imposed tolerance limits.

This work introduces the occupant's Comfort and Well-being Module which comprises a low-cost autonomous wearable wrist device. The device mounts sensors to capture physiological, motion and environmental data. Data is processed to extract various features towards formulating occupants' respective profiling. Moreover, a user-friendly web-application is provided to the occupants that allows a further enhancement of their profile. Occupants can insert information, such as clothing insulation, to optimize the output of the module. Then, the occupant's TC level is assessed over the 7-pointed scale, as proposed by ASHREAE-55 Standard which in turn is used as a decisive for the determination of energy needs [6]. The specific approach grounds on occupant's activity status to approximate the corresponding METs (Metabolic Equivalent of Task), indoor environmental conditions (temperature and humidity) and clothing insulation. Additionally, to the depiction of thermal tolerance limits, the occupant can populate the system with the desirable upper energy cost bounds, therefore, in case the energy cost needed to reach the ideal thermal condition is within the affordable range, the conditions will be set to the ideal. Otherwise, if it exceeds the bounds, it will work on the extreme tolerable conditions provided.

2 THERMAL COMFORT AND WELL BEING STANDARDS

2.1 ASHRAE-55 Standard – Thermal Comfort

ASHRAE has issued the "ASHRAE-55 Standard: Thermal Environmental Conditions for Human Occupancy" which establishes environmental conditions within an indoor space to achieve acceptable thermal comfort for a specified fraction of occupants. ASHRAE-55 is a widely acceptable Standard, adopted to assess the thermal comfort in indoor environments. The Standard was first published in 1966, and to date, numerous revised and updated versions are available that reflect the latest results from field experiments regarding the thermal comfort. Our work has been based on the ASHRAE-55 version, published in 2010 [6].

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment, accomplished by maintaining the heat balance between the human body and the surrounding environment. Any heat gain or loss leads to substantial discomfort thus to maintain a satisfactory thermal comfort level the heat production and heat loss should be equivalent. Thermal comfort and indoor quality levels are critical not only for health matters [7], [8] but also for the productivity of the occupants since it affects individuals' efficiency [9]. Both physiological and psychological parameters affect TC. The quantification of psychological parameters is hard due to the subjectivity of individuals. ASHRAE-55 assesses thermal comfort employing only parameters that can be measured or objectively evaluated, i.e., physiological parameters. Note that ASHRAE-55 can be applied only within indoor spaces, where humans spend more than 90% of their daily routine.

As mentioned before, the thermal satisfaction level is a combination of psychological and physiological parameters. However, ASHRAE-55 considers only the later. From the ensemble of physiological parameters, ASHRAE-55 makes a further classification into primary factors that have a strong impact on the thermal comfort and non-primary factors which slightly affect the thermal comfort level. More specifically, the Standard considers six primary factors that can be divided into environmental and personal ones. Environmental factors can be accurately and objectively measured by sensors and devices within the indoor space, whereas personal factors require manual actions by occupants. The environmental and personal factors required for the assessment of thermal comfort according to the ASHRAE-55 Standard are listed below:

Environmental factors:

- Air Temperature, defined as the average temperature of the air that surrounds the occupant's body uniformly. Otherwise, in non-uniform cases, the Air Temperature is considered as the spatial average and is calculated as the average Air Temperature at head, waist, and ankle level.
- Relative Humidity, defined as the average moisture level of the air that surrounds the occupant's body uniformly.
- Radiant Temperature, defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure.
- Air Speed, defined as the average speed of air that surrounds the occupant's body uniformly.

Personal factors:

- Metabolic Rate, defined as the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism.
- Clothing Insulation, defined as the thermal insulation provided by garments and clothing ensembles.

2.2 Predicted Mean Vote (PMV)

PMV Method proposes a stationary model to predict TC based on the theoretical basis of the Fanger's Method. This model is the most used thermal sensation metric within indoor spaces. A mathematical formula that combines quantitatively environmental and personal factors is employed for the determination of TC. The prediction is an index value within the range of -3 (Cold) to +3 (Warm) and neutral conditions stand at 0 (Neutral). More specifically, PMV uses a 7-points scale, known as ASHRAE-55 Thermal Scale, with seven (7) discrete thermal conditions; Warm, Slightly Warm, Neutral, Slightly Cool, Cool and Cold. The thermal satisfaction level maximizes when the index value of PMV converges to 0 (Neutral) and minimizes when index value reaches the edge values of +3 (Warm) or -3 (Cold). The typical PMV index values of thermal satisfaction are within the range of -0.5 to +0.5. In this range, only the 10% of the occupants are dissatisfied with the thermal environment.

3 COMFORT AND WELL-BEING MODULE

The Comfort and Well-being Module aims to infer as unobtrusively possible the occupants' personal TC level on the thermal scale provided by ASHRAE 55 Standard, utilizing physiological, activity, and environmental data collected by sensors. All the sensors are mounted on a wrist wearable device. This device transmits the data wirelessly to the back-end side of a web-application where the occupants' TC level is determined by applying the PMV calculation. The web-application comprises a front-end in the form of a Graphical User Interface (GUI) that visualizes data, allows users to interact with their data and insert their personal preferences.

Table 1: Description of parameters transmitted by the wearable device

Parameter	Description	Units
HR	Heart rate	bpm
AL	Activity Level	-
MET	Metabolic Rate	Met
Temperature	Air Temperature	^oC
Pressure	Atmospheric Pressure	hPa
Humidity	Relative Humidity	%
Lux	Luminosity Level	Lux
eCO_2	Equivalent Carbon Dioxide Concentration	ppm
TVOCs	Total Volatile Organic Compounds	ppb
Acoustic	Noise Level	db

3.1 Wearable Device

The wearable device is the core component of the Comfort and Well-being Module as the whole system operation is based on the data produced by this device. It is equipped with appropriate sensors which measure both the occupant's physiological and environmental parameters. The wearable is an easy-to-use, comfortable, and user-friendly device which can be placed on the user's wrist in the form of a watch. The optical sensor which is used by the wearable device records the physiological parameter of Heart Rate (HR), the value of which enables the control of the user's physical condition. Photoplethysmography (PPG) is used to calculate HR, which is a non-invasive optical technique for unobtrusive monitoring of changes in the blood flow dynamics. Utilizing the acceleration data an activity classification is being performed, through which a metabolic rate value (met) is calculated. The recorded environmental parameters involve Air Temperature (T), Relative Humidity (H), Atmospheric Pressure (P), Noise Level (N), Luminosity Level (L), Equivalent Carbon Dioxide Concentration (eCO_2) and Total Volatile Organic Compounds (TVOCs). The wearable device transmits the measurements collected by its sensors wirelessly employing Wi-Fi technology so as to allow data flow to the back-end side. The back-end collects the data by the wearable device along with the data that the user inserts directly to the application, such as the clothing Insulation (clo) value, to predict the PMV.

The wearable device implements the HTTPS protocol to securely transmit the data via Wi-Fi to the web-application's server. The payload is sent per minute and its parameters are described in Table 1, while its form is as follows: HR | AL | MET | TEMPERATURE | PRESSURE |HUMIDITY | LUX | eCO2 | TVOCs | ACOUSTIC

3.1.1 Hardware Components. The hardware of the device incorporates the ESP-WROOM-32 module by Espressif [10], a low-cost, low-power system on a chip microcontroller with integrated Wi-Fi and dual-mode Bluetooth. The ESP32 deploys a Tensilica Xtensa dual-core 32-bit LX6 microprocessor, upon which the whole software of the device is executed. With regard to the sensors which are integrated, the printed circuit board of the device includes the MAX30105, a high-sensitivity optical sensor able to continuously obtain the PPG signal [11]. An ultra-low power, 3-DOF MEMS accelerometer with measurement ranges of ±2g, ±4g, and ±8g by Analog Device, the ADXL362 acceleration sensor [12], is also mounted on the device. Finally, the hardware comprises the Bosch BME280 MEMS sensor for the concentration of ambient T, H and P, the sCioSense CCS811 sensor responsible for measuring the TVOCs and eCO2, the AMS TSL2591 sensor for measuring indoor brightness, L, and the siSonic's SPW2430 sensor for measuring environmental noise, N. The printed circuit boards of the device as well as its experimental casing are depicted in Figure 1.

3.1.2 HR measurement. The device uses the PPG method to extract the desired physiological parameters from the wrist. The PPG method is often used in wearable devices as it is a non-intrusive method of assessing physiological parameters. The main challenge of the implementation stems from the various motion artifacts (MAs) that appear due to any type of movement of the user and impose noise on the signal. Stronger and more complex MAs are introduced in the PPG signals recorded on the wrist, compared to those recorded from other parts of the body, due to the flexibility and physiology of the wrist [13]. Consequently, the PPG signal presents low amplitude, and when the noise that appears is higher than the signal itself, a significant distortion of the latter takes place, and its parameters are deemed invalid even after imposing a filter. This module implements an effective algorithm for the digital processing of the PPG signal in the time domain to remove the corresponding MAs. Aiming at a lightweight system, this algorithm was specifically designed to require no significant processing power. Given the fact that the useful frequencies of the PPG signal are in the range of 0.5-5.0 Hz, a bandwidth filter with cut-off frequencies [0.5, 5] Hz is applied [14], which eliminates the noise caused by the movement as well as the high-frequency noise imposed by the ambient light. Concluding, the aforementioned filter accomplishes the removal of the baseline wandering and the reduction of much of the noise.

For the calculation of HR, the filtered IR signal is used since a single light source is sufficient for that particular measurement [15]. A peak detection algorithm detects the peaks of the signal, and in turn calculates the value of the beats per minute (BPM) for each pair of successive peaks according to the equation below.

$$HR = \frac{Fs}{d} * 60\ bpm$$

Figure 1: Wearable Device Printed Circuit Board

Table 2: Activity categorization with corresponding met values (ASHRAE standard)

Activity	Intensity	MET
Lying down, seated quietly (i.e., watching tv)	<50	1
Sedentary activity (i.e., office work)	50 -200	1.2
Light Activity (i.e., walking, household chores)	200-350	1.6
Medium Activity (i.e., moderated effort home exercise)	350 – 550	2
High Activity (i.e., vigorous exercise)	>550	2.5

where the frequency Fs equals 25 Hz and d is the time difference between two consecutive peaks. Finally, HR is obtained as the average of all the individual values in the span of a minute.

3.1.3 MET Value. With the aim to classify the movement in categories as dictated by the ASHRAE-55 Standard depicted in Table 2, the accelerometer is deployed. Using the existing 3-DOF accelerometer which is integrated in the microcontroller board, the subject's body and hand movements are obtained. The activity level is determined from the device's average acceleration during specific time intervals on the three-dimensional space. Aiming to calculate the distance covered from three-dimensional acceleration data, the Euclidean distance for the three dimensions is measured with the following equation.

$$Acc = \sqrt{Acc_x + Acc_y + Acc_z}$$

Then the double integral is calculated. In this work a method to remove the gravity factor via differentiation and integration of the collected data has been used before calculating the Euclidean distance. Based on the collected experimental data, thresholds have been set, determining the aggregations of values that belong to each category. In this way, distinction between the movement intensities is taking place, thus enabling activity classification.

3.1.4 Environmental Data. The values of the environmental parameters are recorded directly by the environmental sensors which are mounted on the wearable device. No further data process is needed.

3.1.5 Technological status for daily activity monitoring and environmental conditions. Table 3 lists wearable devices which are capable of monitoring environmental conditions. The first one is implemented in an academic context as a wearable tool catered towards asthma research, while the rest are commercially available devices for personal air exposure monitoring. Clearly, there is a lack of wrist wearables which can detect environmental conditions along with personal physiological factors, like the device proposed in this paper.

3.2 Back-end Structure

3.2.1 Database. At the back-end side of Comfort and Well-being Module stands a database that collects and stores the occupants' data, as transmitted by the wearable device. This data are combined with manually inserted data by the occupant, such as the clothing insulation, to determine the PMV value. An instance of records from the database is presented in Table 4.

3.2.2 Clothing Insulation Parameter. Clothing insulation describes the ability of the clothes to insulate the heat exchange between the skin and the environment outside the clothes and is expressed in units of clo. Clothing ensembles and garments insulate the heat transfer between the human body (skin) and the environment. The thermal insulation has a strong impact on the occupant's TC thus, an accurate input of the occupant's outfit is necessary. However, the accurate and continuous monitoring and measurement of the occupants' insulation level consists of a non-viable solution, as it requires the installation of a complex and expensive device ecosystem

Table 3: Wearable devices for daily activity and environmental conditions monitoring

Wearable Device	Measured Parameters
ART/Asthma Research [16]	Ozone
	Total Volatile Organic Compounds (TVOCs)
	Humidity
	Activity Level
	Wrist-worn
	Data on flash can be transferred through BLE
	App manages data and provides cloud access for secure storing
Atmotube Plus/ATMO [17]	Volatile Organic Compounds (VOCs)
	Atmospheric Pressure
	Environmental temperature
	Air Humidity
	Attachable, lightweight, long-lasting battery
	Dedicated Atmotube App
AerBand / AerNos [18]	Wearable or attachable air pollution monitoring
	Step Tracking
	Ozone
	Ammonia
	Indoor volatile Organic Compounds (VOCs)
	End User app for Android and IOS smartphones for tracking RT exposures
	AerBand Data Cloud Platform access for environmental data handling

within the apartment. Thus, ASHRAE-55 Standard proposes methods to assume the clothing insulation value based on predefined common clothing ensembles, such as typical winter and summer outfits, and individual garments. During the initialization process of the web-application, the occupant inserts the clothing insulation through the GUI. As clothing insulation has a significant impact on determining TC, a user-friendly front-end has been developed to increase the occupant's engagement rate with the Comfort and Well-being Module and smoothly update the clothing insulation in regular intervals. The clothing insulation requires a two-step process from the occupant, as can be seen in Figure 2 and Figure 3. First, the occupant must choose between four predefined typical outfits, one for each season - summer, winter, spring, and autumn outfit. Then, the occupant can adjust the garments of the predefined outfits to decrease or increase the insulation level as proposed by the typical outfits. More specifically, the occupant can update the settings of each typical outfit through a series of dropdown lists and submit changes to update the clothing insulation parameter of the PMV method.

3.2.3 PMV Calculation. PMV employs a mathematical model to quantify the TC within an indoor space. The model is described by the equation below. The determination of PMV requires the execution of a series of intermediate steps related to unit transformation, derivative quantities calculation from the primary factors (i.e., environmental, and personal factors) and variables corresponding to the heat exchange between the body and the surrounding environment calculation.

$$PMV = \left(0,303e^{2,1*M} + 0,028\right) * [(M-W) - H - Ec - Cres - Eres]$$

where:
M - Metabolic Rate,
W - External Work which is commonly considered equal to 0 met,
H - Sensitive Heat Losses,
Ec - Heat Exchange by Evaporation on the Skin,
Cres - Heat Exchange by Convection in Breathing and
Eres - Evaporative Heat Exchange in Breathing.

Table 5 lists the data utilized by the proposed Comfort and Well-being Module to predict the PMV value. It must be noted that we consider two assumptions regarding the environmental factors. The first assumption is related to Globe Temperature [t_g] and the second one is related to Air Velocity [A_v]. More specifically, we consider the Globe Temperature [t_g] equal to Air Temperature [T_a] and Air Velocity [A_v] equal to zero. These assumptions do not have significant impact on the PMV output, since we get a value on the same discrete range of values.

3.2.4 Energy Cost Bounds. Energy cost bound preferences allow the occupant to choose the range in terms of the affordable cost amount for a specified period (in this case the specified period is a month). The kWh unit cost is parsed automatically by an API endpoint and can be manually updated by the occupant. These pre-defined set of options are populating the appropriate database while the corresponding algorithmic thread of the Comfort and Well-being module determines whether the energy cost needed to reach the ideal thermal condition is within the affordable range or it will work on the extreme tolerable conditions provided and notifies the occupant accordingly. The Energy Cost Bound algorithmic thread accesses continuously historical consumption data as well as current metering and submetering consumption data.

The GUI for these preferences can be accessed, after the proper authorization of the occupant, through a drop-down menu comprising mainly UI Slider elements to optimize the user experience, rather than complex and confusing UI Dropdown and Checkbox elements, as shown in Figure 4.

Table 4: An instance with records from the web-application's database

Date	Acoustic(db)	Visual(lux)	TVOCs (ppb)	CO2(ppm)	IndoorTemp. (°C)	IndoorHum. (%)	Met.Rate (met)	PMV	PMV	OutdoorTemp (°C)
21-12-21 14:13:08	41	310	35	634	21.75	52.53	1.2	0.41	Slightly Warm	19.6
21-12-021 14:12:05	42	330	4	427	21.56	53.2	1.0	0.01	Slightly Warm	19.6
21-12-21 14:11:01	44	340	6	445	21.4	53.5	1.0	-0.01	Slightly Cool	19.6
21-12-21 14:10:00	42	341	11	477	21.2	54.1	1.0	-0.05	Slightly Cool	19.5
21-12-21 14:08:59	41	341	12	482	21.1	55.3	1.0	-0.07	Slightly Cool	19.5
21-12-21 14:07:57	42	342	38	653	20.9	55.7	1.0	-0.12	Slightly Cool	20.1
21-12-21 14:06:56	43	343	5	436	20.6	56.5	1.0	-0.18	Slightly Cool	20.1
21-12-21 14:05:55	42	343	44	690	20.2	56.8	1.0	-0.26	Slightly Cool	20.1
21-12-21 14:04:54	41	345	46	706	20.0	57.2	1.0	-0.3	Slightly Cool	20.1
21-12-21 14:03:52	42	345	18	519	19.9	58.6	1.0	-0.31	Slightly Cool	20.0
21-12-21 14:02:51	43	344	75	897	19.8	58.3	1.0	-0.35	Slightly Cool	20.0
21-12-21 14:01:50	43	342	14	495	19.3	59.8	1.0	-0.44	Slightly Cool	20.0
21-12-21 14:00:48	40	341	12	485	19.2	60.6	1.0	-0.46	Slightly Cool	20.3
21-12-21 13:59:47	41	342	12	485	18.8	60.3	1.0	-0.55	Slightly Cool	20.4
21-12-21 13:58:46	41	344	33	617	18.8	61.1	1.0	-0.54	Slightly Cool	20.4
21-12-21 13:57:45	40	347	24	560	18.6	61.9	1.0	-0.6	Slightly Cool	20.4
21-12-21 13:56:44	41	349	14	495	18.1	64.2	1.0	-0.67	Slightly Cool	20.4
21-12-21 13:55:42	41	351	8	459	17.9	64.6	1.0	-0.72	Slightly Cool	19.7
21-12-21 13:54:41	42	353	41	671	17.5	65.0	1.0	-0.81	Slightly Cool	19.7
21-12-21 13:53:40	40	352	42	682	17.2	66.3	1.0	-0.86	Slightly Cool	19.7
21-12-21 13:52:38	40	354	31	605	17.1	66.9	1.0	-0.9	Slightly Cool	20.0

4 EVALUATION - DISCUSSION

The content of this work enables occupants to perform efficient energy demand management by ingeniously combining their TC level with thermal sensation tolerance as well with energy cost bounds. More specifically, we introduce a low-cost wrist wearable device that incorporates sensors capable of continuously record physiological data, such as the heart rate, activity, and indoor environmental data. Then, the collected information is transmitted to the back-end structure, where in conjunction with the personalized parameters provided manually by the occupant, the PMV value is calculated, and the TC level of an occupant is revealed while the thermal tolerance limits are set. Additionally, when the occupant inserts the desirable upper energy cost bounds, the system utilizing historical and current energy consumption data, checks

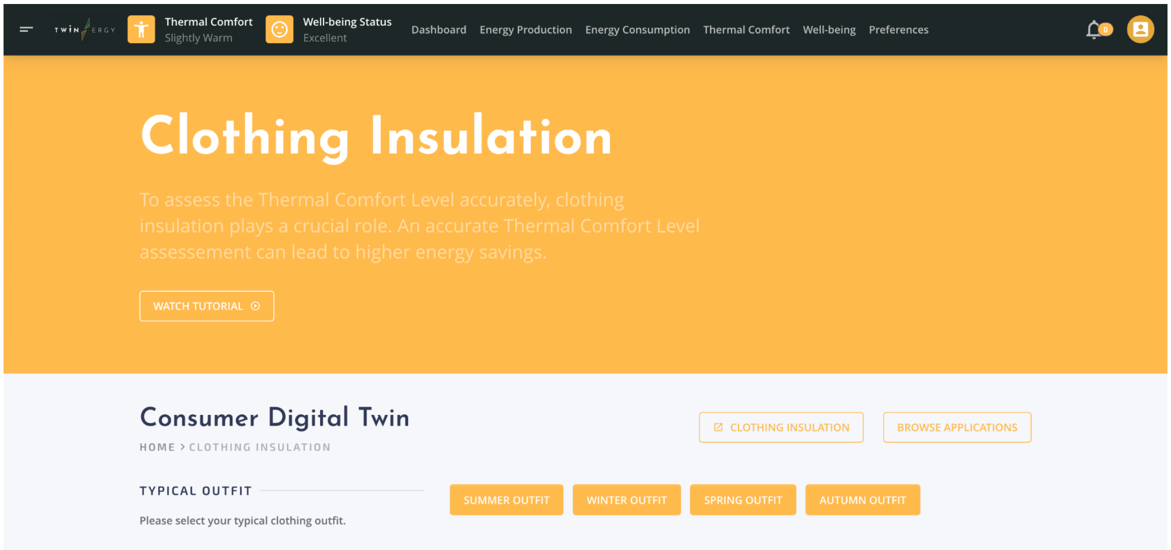

Figure 2: GUI for inserting the clothing insulation (1)

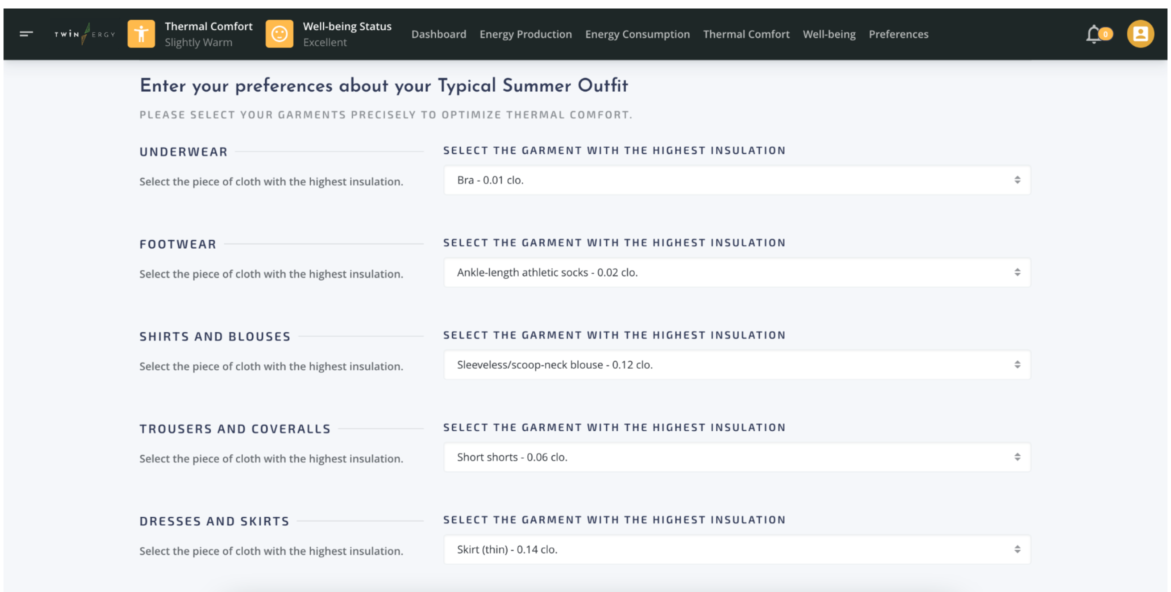

Figure 3: GUI for inserting the clothing insulation (2)

continuously whether the energy needed to reach the ideal thermal condition is within the affordable range, and if not, it operates within the extreme tolerable conditions provided.

The evaluation process of the entailed system included 4 subjects, yielding a total of 20 hours of data. The test subjects were provided with an endpoint to state their perceived thermal sensation, which was compared with the PMV value to evaluate the system's accuracy. Although the results were satisfactory, a broader set of different indoor environmental conditions in a larger population sample must be included to ensure overall accuracy.

Further improvements are currently being developed and will be included in a future version of this work. The quantification of the occupant's activity benefits drastically from the fusion of heart rate and acceleration data. Heart rate fluctuations are a direct manifestation of a change in the state of the occupant and when combined with the accelerometer values, would provide a more accurate activity profiling and in turn a more accurate thermal comfort level identification.

The parameters provided by the proposed device act as breeding ground for the assessment of the overall indoor environmental quality. The Indoor Air Quality (IAQ) index which is derived from

Table 5: Data utilized by the proposed Comfort and Well-being Module

Factor	Units	Symbol	Source	A/M
Environmental Factors				
Air Temperature	^oC	t_a	Wearable Device	Automatic
Relative Humidity	%	Rh	Wearable Device	Automatic
Air Velocity	m/s	A_v	Wearable Device	Automatic
Globe Temperature	^oC	t_g	Wearable Device	Automatic
Personal Factors				
Clothing Insulation	clo	I_{cl}	Occupant	Manual
Metabolic Rate	met	M	Wearable Device	Automatic

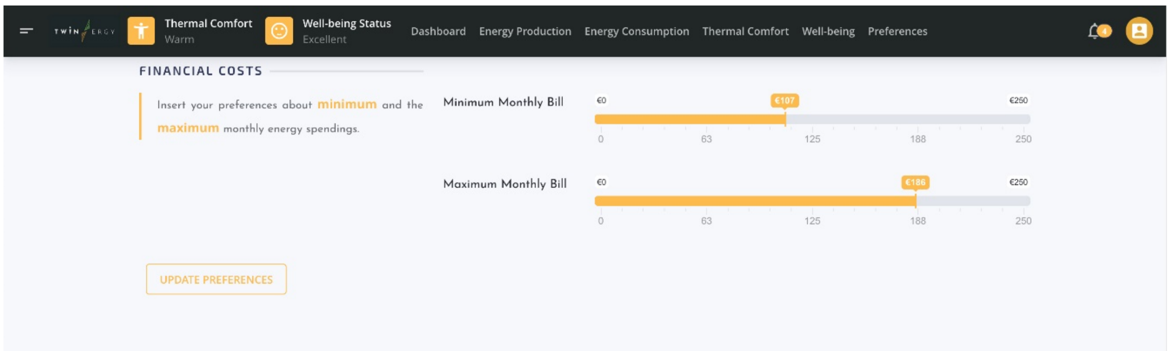

Figure 4: GUI for inserting energy cost bounds

the acquired TVOC and eCO2 values, combined with the thermal comfort level, as well as the acoustic and visual comfort are the determinants for the IAQ index. The latter has proven to be a significant factor that influences the occupants' health, comfort, productivity, and general well-being. Thus, its extraction, specifically in the context of a wearable device, will be a significant contribution to the current implementation.

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