TWIN ERGY

Consumer well-being module

D7.2

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Deliverable

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✓	**P**	**Public**
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Statement of Originality

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Nomenclature

Abbreviation	Explanation
API	Application Programming Interfaces
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BSN	Body Sensor Network
CDT	Consumer Digital Twin
CI	Clothing Insulation
CO_2	Carbon Dioxide
DNA	Deoxyribonucleic Acid
eCO_2	Equivalent Calculated Carbon Dioxide
FPGA	Field-programmable gate array
FPGA	Field-Programmable Gateway Array
HR	Heart Rate
LoRaWan	Long Range Wide Area Networks
MAC	Media Access Control
MR	Metabolic Rate
PCB	Printed Circuit Board
PDA	Personal Digital Assistant
PDA	Personal Digital Assistant
PMV	Predicted Mean Vote

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Abbreviation	Explanation
PPD	Predicted Percentage of Dissatisfied
PPG	Photoplethysmography
RNA	Ribonucleic Acid
TC	Thermal Comfort
TVOCs	Total Volatile Compounds
WHO	World Health Organisation

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Summary

The deliverable D7.2: Consumer well-being module is implemented under the framework of T7.2: Consumer Comfort / Well-being Module within the Work Package 7: Development of TwinERGY system Modules. It describes the consumers' comfort / well-being module comprising a low-cost autonomous wearable device through which specific physiological, motion and environmental data can be unobtrusively collected and aggregated and the appropriate software to process this data and extract various features towards formulating a consumer's comfort and well-being profile. Moreover, user-friendly applications and APIs are introduced, that allow consumers to fine tune their profile with extra information such as clothing conditions, mean radiant temperature and outdoor environmental conditions.

The current document is divided into five different sections that can be summarized as follows:

- Section 1 introduces the scope of this document as well as its contents.
- Section 2 analyzes wearable systems used to collect physiological parameters and environmental conditions.
- Section 3 depicts the wearable platform, its interfaces, and its communication capabilities.
- Section 4 describes the assessment of the Thermal Comfort level (TC) and Well-Being status as well as the related standards.
- Section 5 describes the deliverable conclusions and main outcomes.

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1. Introduction

TwinERGY introduces a first-of-a-kind Digital Twin framework that incorporates the required intelligence for optimising demand response at the local level without compromising the well-being of consumers and their daily schedules and activities. The main idea behind the conception of the TwinERGY project lies in the interest of the project partners to exploit the new business opportunities that project implementation delivers and increase the relevance of the DR optimization tools and strategies in the new generation of energy management systems.

By coupling mature practices for citizen engagement with service innovation through the lenses of public value, TwinERGY will ensure that a wide range of the interests of consumers/prosumers will be represented and supported in the energy marketplace. In this context, TwinERGY will develop, configure and integrate an innovative suite of tools, services and applications for consumers, enabling the increase of awareness and knowledge about energy consumption patterns, behaviours, generation/demand forecasts and increase of local intelligence via properly established Digital Twin-based Consumer-Centric Energy Management and Control Decision Support mechanisms that locally optimise demand response. Key use cases will be trialled across 4 pilot regions making use of cutting-edge methods and tools. Special focus is given on standardisation and policy & market reform as key enablers for the successful commercialization of the TwinERGY results. Additional attention is given towards establishing knowledge transfer and exchange synergies with similar projects listed under the BRIDGE Initiative, while explicit focus will be given on the establishment of close collaboration with the projects funded under the LC-SC3-ES-5-2018 topic, to further reinforce and catalyse collaborative advancements in research, innovation, regulatory and market issues around Demand Response, RES Integration and Consumer Engagement.

This deliverable aims to provide the required means to accurately depict the comfort / wellbeing level of the consumers rendering them predictable energy wise and allow pertinent personalised feedback notifications for optimal energy management while preserving comfort and well-being levels. Specifically, a wearable wrist device collects the consumer's physiological, motion and indoor environmental data using unobtrusive appropriate sensors. Furthermore, taking the clothing conditions and the mean radiant temperature into consideration, the consumer's TC level as well as the indoor air quality is assessed based on the categorization provided by the ANSI/ASHRAE 55-2010 Standard [1]. TC and indoor quality levels are critical not only for health-related reasons but also for the productivity of the occupants since they affect the individuals' efficiency as well as their mood. Being aware of the occupant's TC level, the indoor quality level and outdoor conditions, essential projections can be drawn regarding energy demand flexibility.

1.1 Scope of this deliverable

People spend more than 80% of their time in indoor environments[2]. Suitable TC plays a significant role in their physical and physiological wellbeing 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[4],[5]. Ensuring a comfortable and healthy indoor environment is of great importance for occupants, as it affects their well-being, productivity, and efficiency.

[1] American Society of Heating, Refrigerating and Air-conditioning Engineering. Thermal Environmental Conditions for Human Occupancy; ANSI/ASHRAE Standard 55-2010; American Society of Heating, Refrigerating and Air-conditioning Engineering: Atlanta, GA, USA, 2010. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

[2] Richard de Dear, G. S. Brager. 1998. Developing an adaptive model of thermal comfort and preference.

[3] Jacqueline Vischer. 2007. The effects of the physical environment on job performance: towards a theoretical model of workspace stress. Stress and Health. 23(3):175–184. DOI:10.1002/smi.1134

[4] International Energy Agency, Directorate of Sustainable Energy Policy and Technology. Transition to sustainable buildings: strategies and opportunities to 2050. Published by Organization for Economic Co-operation and Development (OECD), 2013.

[5] Energy consumption in households, Eurostat EU 2019, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households

Thermal sensation (TS) and TC relate to the living environments and the life of the occupants. TC, which expresses the personalized thermal satisfaction associated with the thermal environmental conditions, includes an ideal thermal condition and the corresponding tolerance limits on either side which the occupant remains comfortable, while well-being status concerns the quality of indoor air in terms of pollutants. Continuously determining occupants' TC and wellbeing 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[6]. It is indispensable to enable occupants to depict their own personalised tolerance limits while continuously assessing TC in an automatic manner. It is therefore imperative to provide unobtrusive means to accurately determine the personalised TC / wellbeing level of the occupants to make them predictable energy wise and allow pertinent personalised feedback for optimal energy demand management while preserving the imposed tolerance limits.

This deliverable introduces the consumers' comfort / well-being module comprising a low-cost autonomous wearable wrist device using appropriate sensors through which specific physiological, motion and environmental data can be unobtrusively obtained and appropriate software to further process them to extract various features towards formulating consumers' respective profiling. Moreover, user-friendly applications are provided allowing the occupants to further enhance their profiling with extra information such as clothing conditions, outdoor environmental conditions, and mean radiant temperature. Then, accounting the indoor conditions the occupant's TC level is assessed on the scale provided by ASHRAE 55 STD [4] which in turn is used as a decisive factor for the determination of energy needs. The specific approach is based on the user's activity status to approximate the corresponding METs (Metabolic Equivalent of Task) and accounting indoor conditions (temperature and humidity), clothing insulation and other

[6]Vassilis Stavrakas, Alexandros Flamos. 2020. A modular high-resolution demand-side management model to quantify benefits of demand-flexibility in the residential sector. Energy Conversion and Management. https://doi.org/10.1016/j.enconman.2019.112339

parameters the TC is predicted thus making the ideal thermal condition adjustable. 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 to reach the ideal conditions 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.

1.2 Structure of the document

- ANALYSIS STUDY FOR WEARABLE SYSTEMS COLLECTING PHYSIOLOGICAL PARAMETERS and ENVIRONMENTAL CONDITIONS

This section provides an analysis of the current technological status of wearable systems for the collection of physiological and environmental parameters. A definition of the concept and objectives of a wearable recording system, the network and communication protocols used by these systems, as well as issues related to security, privacy and reliability of wearable systems. The subsystems of the developed wearable device for the collection of physiological and environmental parameters are presented too. This section is structured as showing below:

- Sensors
    - Biomedical Sensors
    - Integration of biomedical sensors in wearable systems
- Current Technological Status of Wearable Systems collecting physiological parameters and environmental conditions
    - Daily Activity Monitoring Devices
    - Daily Activity Monitoring Devices including Environmental conditions
- Network and Communication Protocols
- Security, Privacy and Reliability of Wearable Systems
- Implementations in the framework of the Comfort and Wellbeing Module

- WEARABLE PLATFORM, INTERFACES AND PROTOCOLS

This section depicts the functional and non-functional specifications of the wearable platform, its hardware and software components, as well as the tests conducted with the aim to evaluate the measured parameters. Network and communication protocols and user interfaces are also presented. This section is structured as showing below:

  - Wearable Platform
    - Functional and non-Functional System Specifications
    - Wearable Device Hardware
    - Wearable Device Software
    - Measurement evaluation
  - Graphical User Interfaces and Protocols
    - Graphical User Interfaces
    - Protocols

- THERMAL COMFORT AND WELL BEING STANDARDS

This section presents the ASHRAE-55 Standard Guidelines for TC and the regulatory frameworks incorporated by ASHRAE-61 Standard for Indoor Air Quality. The assessment of the individual's TC level results from the PMV Method which is presented in detail, too. This section is structured as showing below:

  - ASHRAE-55 Standard - Thermal Comfort
    - Introduction
    - Thermal Comfort
    - Factors affecting Thermal Comfort
      - Environmental Factors
      - Personal Factors
    - PMV Method
    - PPD
  - ASHRAE Standard - Indoor Air Quality

1.3 Audience

The present document (along with its updated versions) is a public deliverable, which is addressed to the TwinERGY consortium partners, the European Commission services and everyone interested in the rules and procedures of data management in the TwinERGY project and will be published through all the appropriate channels.

2. Analysis of Systems Measuring Physiological Parameters

2.1 Sensors

A sensor is a module which detects a physical quantity and produces a measurable output related to that quantity. Sensors are used in everyday objects, such as touch-sensitive elevator buttons and light bulbs which emit brighter or softer light while touching their base. There are countless uses and applications in which sensors are incorporated such as in cars and machines, in the field of aeronautics, medicine, industry and robotics.

There are different classifications of sensors:

- One classification distinguishes active and passive sensors. Active sensors are those which require an external excitation signal or a power signal (e.g., LiDAR-light and range detection, photoconductive cell). Passive sensors, on the other hand, do not require any external power signal. They produce an immediate output response (e.g., radiometers, film photography).
- Another type of classification is based on the detection means which are used by the sensor. Some detection means are electrical, biological, chemical and radioactive.
- One more classification is based on the conversion effect, i.e. input and output. Some of the common conversion phenomena are photoelectric, thermoelectric, electrochemical, electromagnetic and thermoplastic.
- Finally, there are analog or digital sensors. Analog sensors produce an analog output, i.e., a continuous output signal in relation to the quantity being measured. Digital sensors, in contrast, work with discrete or digital data.
- According to the application and the parameters which sensors measure, they can be classified as (the list is not exhaustive):
    - Temperature sensors

- Proximity sensors
- Accelerometers
- Infrared sensors
- Pressure sensors
- Photodetector
- Ultrasound sensors
- Smoke, Gas and Alcohol sensors
- Touch sensors
- Biomedical Sensors
- Humidity sensors
- Humidity sensors
- Flow and Level sensors

2.2 Biomedical sensors

Biomedical sensors are used to obtain information about the body. They are divided into sensors for physiological parameters, sensors for chemical parameters and biosensors. The sensors for physiological parameters are used to record blood pressure, body temperature, blood flow, blood viscosity, heart rate and respiration. The sensors which record chemical parameters are used to detect concentration of a body fluid, such as pH value, calcium (Ca^{+}) concentration and glucose concentration. Biosensors are used to detect enzymes, antigens, antibodies, hormones, DNA, RNA and microbes.

Nowadays, the use of biomedical sensors prevails in clinical medicine. Modern patient care utilises such sensors both for monitoring and diagnostic procedures. Accurate medical diagnostic procedures require strict specifications for the design and use of a biomedical sensor. The packaging materials of such sensors are also critical elements of the design process. Some other technical requirements demand mechanical strength, electrical safety, and size reduction of the sensor.

2.2.1 Integration of biomedical sensors in wearable systems

The growth of wireless technologies along with the constant improvement of sensors' design can alter the conventional healthcare system. Wearable healthcare systems which provide continuous physiological data and consequently information about individuals' general health can complement or even improve the current healthcare procedures. Wearable systems that collect physiological parameters can effectively enhance the care system in hospitals, acting as smart medical assistant which help physicians manage their patients' data flows, react promptly, and make calculated decisions. What is more, these systems provide the opportunity for patients to receive appropriate and immediate treatment. Alongside these benefits, they can be used for remote monitoring of individuals, improving the quality of the lives of both patients and healthy individuals. Such systems contribute to the reduction of healthcare costs as they can provide continuous monitoring of patients, automate several medical procedures and prevent diseases.

Portability is a prime advantage of wearable systems. As a result, wireless sensors need to be small, lightweight, and low power. In addition, wearable systems should provide the capability for transferring the collected data, making them available to the external world. Obviously, a wearable system must address issues regarding the communication level, such as communication protocols, antennae design and signal propagation. Ultimately, the crucial factors that need to be met are the design of reliable sensors, reliable data transmission, privacy and security for users.

2.2 Technological Status of Wearable systems collecting physiological parameters

Wearable devices are smart electronic devices that are placed on the body and monitor whoever is wearing them and / or his environment. These devices prevail in the Industrial Internet of Things (IIoT). They allow the exchange of data over the Internet with a manufacturer, operator and / or other connected devices, without the need for human intervention. The communication is settled either directly via a built-in wireless connection or through other devices, such as a mobile phone. The user's physiological or environmental data are being processed either in a processing unit located on the wearable or on an external server. Modern materials, designs, energy storage technologies and new production techniques lead to improvements in efficiency, functionality and usability of wearable systems. Wearable devices can:

- monitor and facilitate people's lifestyles,
- assist in specialised personal and business activities as they include built-in intelligence and seamless connectivity,
- provide status / activity monitoring,
- feedback and activation / delivery services (e.g., drug delivery or stimulation),
- tracking,
- identification,
- personal alerts,
- information display and
- virtual assistance

The range of applications in which they can be incorporated is potentially unlimited (health, sports, industry, robotics, etc.).

2.2.1 Wearable devices for daily activity monitoring

The widespread use of cost-effective wearable devices along with applications for mobile phones and computers makes it possible to monitor and access daily physical activity data in a wide open and connected environment, that of the Internet of Things (IoT).

Table 1 shows some of the most popular commercially available wearable physical activity trackers.

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Product/Manufacturer	Measurements/Characteristics	Picture
Charge 3 / Fitbit [7]	• HR • Calories • Steps • Activity recognition (running, swimming, sports, etc.) • Ability to choose from over 15 modes of exercise such as running, cycling, swimming, yoga and much more, set goals and receive statistics in real time • Sleep quality and stages • Battery life over 7 days • GPS connection for tracking routes and distances • Call and calendar alerts, message alerts and quick answers, app updates	
Vivosmart 4 / Garmin [8]	• HR • HRV and stress levels • SpO_2 • Calories • Sleep monitoring • Activity recognition (walking, running, training, yoga, swimming in the pool, etc.) • Mobile application (Garmin Connect app) • Call and message notifications • Battery life up to 7 days	
Gear Fit2 Pro / Samsung [9]	• Automatic exercise detection • Calories • HR • GPS • Music • Call and message notifications • Diet monitoring • Bluetooth v4.2 • Battery life for days	

[7] https://www.fitbit.com/eu/charge3

[8] https://buy.garmin.com/en-US/US/p/605739

[9] https://www.samsung.com/gr/wearables/gear-fit-2-pro-r365/SM-R365NZKAEUR/

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Watch Series 4 / Apple [10]	• Automatic exercise detection • Exercise programs for yoga and hiking • Rate of pace and rhythm alerts • Activity competitions, one-on-one. Sharing activity with friends. Personalised tips. Monthly challenges. Achievement rewards. • GPS • Walkie-talkie, phone calls and messages • Apple Music and Apple Podcasts • ECG from the wrist • Low or high heart rate alerts and arrhythmias • Drop detection and SOS alert • Mobile application • Wi-Fi (802.11b / g / n 2.4GHz) • Bluetooth 5.0 • Battery life up to 18 hours	

Table 1. Wearable devices for daily activity monitoring

2.2.2 Wearable devices for daily activity monitoring and environmental conditions

Table 2 lists devices that are capable of environmental condition monitoring. 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.

ART / Asthma Research Tool [11]	• Ozone • Total Volatile Organic Compounds (TVOCs) • Humidity • Activity Level • Wrist-worn • Data stored on flash can be transferred through BLE • App manages data and provides cloud access for	

[10] https://www.apple.com/apple-watch-series-4/

[11] Developing a Low-Cost Wearable Personal Exposure Monitor for Studying Respiratory Diseases Using Metal–Oxide Sensors, Kyle R. Mallires et al.

	secure storing	
Atmotube Plus / ATMO [12]	• Volatile Organic Compounds (VOCs) • Atmospheric Pressure • Environmental Temperature • Air Humidity • Attachable, lightweight, long-lasting battery • Dedicated Atmotube App	
AerBand / AerNos [13]	• Wearable or attachable air pollution monitoring • Step Tracking • Ozone • Ammonia • Indoor Volatile Organic Compound (VOCs) • End user app for android and IOS smartphones for tracking real time exposures • AerBand Data Cloud Platform access for environmental data handling	

[12] https://atmotube.com/products/atmotube-plus
[13] https://www.aernos.com/aerband-research/

Flow 2 / Plume Labs [14]	• Particulate Matter: PM1, PM2.5, PM10 • Volatile Organic Compounds (VOCs) • Nitrous Oxides (NO_2) • Attachable on clothing or on worn accessories • Typical daily use charge of 24-72h depending on use of Idle mode • Bluetooth Low Energy (BLE) • Flow companion app for storing and visualising the device's measurements • Dimensions: 125mm x 40mm x 35mm • Weight: 70g	

Table 2. Wearable devices for daily activity and environmental conditions monitoring

2.3 Network and Communication Protocols

Wearable devices need to perform a set of telecommunication technologies that will enable the transmission of the measured data to the external world for visualisation or further processing purposes. Physiological data measured by sensors on the body require a two-stage communication to be transmitted to a remote server. In the first stage, a short-range communication protocol is used to transmit data to the nearest gateway node, which can be a mobile phone, computer, custom FPGA or a microcontroller board. The gateway is responsible for the advanced processing of the data as well as for the next stage of long-distance communication, where the processed signal is transmitted to a remote server located in a healthcare unit. In the case of short-range communication, the sensors can communicate directly with the gateway via wireless means. Alternatively, autonomous sensor nodes can form a BSN, usually a network in star topology, and send data to the central node of the BSN. The BSN host then sends the data to the gateway after some processing. The sensors on the body and the BSN hub can communicate using wired or wireless media. However, wired

[14] https://plumelabs.com/en/flow/

connections can impede the mobility of users, and cause frequent failed connections, thus considering them unsuitable for wearable health monitoring systems. On the contrary, wireless technology is being adopted as the most sustainable and reliable solution for short-range communication. The choice of a specific technology depends on the requirements of each application. Table III presents some well-known communication protocols and their characteristics. An overview of the wireless communication protocols is presented below.

Bluetooth is a low-power communication technology that is widely used in devices such as laptops, smartphones and daily activity monitoring systems for short-range data communication. It uses the 2.4 GHz band in the Industrial, Scientific, and Medical (ISM) radio spectrum and transmits signals over 79 specified channels using the Frequency Hopping Spread Spectrum (FHSS) method. The FHSS method is less sensitive to noise and interference and offers extremely secure data transmission. A master device can communicate with seven dependent devices (slaves), forming a star-type network structure based on Bluetooth connectivity (Piconet). The master sets the clock and the hopping sequence for the entire Piconet. Bluetooth technology can support data rates of up to 3 Mbps, depending on the configuration layout, although maximum performance can only reach ~ 2.1 Mbps. For general applications, the transmission distance usually ranges from 1m to 10m. A version of ultra-low-power Bluetooth technology is the Bluetooth Low Energy (BLE) or Bluetooth V4, introduced for mobile devices with limited battery capacity. BLE uses the same frequency band as the conventional Bluetooth technology and transmits over 40 channels with a bandwidth of 2 MHz each. BLE offers low power (~ 10 mW) wireless connectivity being a strong contender for short-range communication in long-term monitoring systems.

Another wireless standard for short-range, low-power, low-cost data communication is ZigBee. It operates at the 2.4 GHz frequency band (worldwide), 915 MHz (America and Australia), 868 MHz (Europe) of the ISM spectrum and transmits data in sixteen, ten and one channel respectively. ZigBee devices can be connected by creating P2P (peer-to-peer), star, tree or mesh network topologies. The transmission range of the ZigBee model is limited to 10-20 m for indoor applications, mainly due to the low output power and the presence of high dielectric materials. However, the range can be increased up to 1500 metres without obstacles. The data rate is much slower compared to Bluetooth technology and can reach a maximum rate of 250 kbps for the 2.4 GHz band. Low data rates may result in limitations of the number of sensors, the number of simultaneous measurements and the quantity of data storage in a multi-sensor network. Nevertheless, the low-power requirement of the ZigBee standard leads to extended battery life, which is beneficial for long-term health monitoring applications.

Other available wireless technologies for short-range communication are IrDA, UWB, RFID, NFC and Wi-Fi. IrDA was one of the most popular wireless communication technologies for very short ranges (<10 cm) due to its high data rate. However, IrDA communicating devices must maintain the line of sight for transmission which makes it useless for wearable monitoring systems. UWB operates at the wide frequency range of 3.1 - 10.6 GHz. It offers a high data rate at a very low power spectral density, which protects it from possible interference with other radio waves. Although the UWB technology is promising, the complexity and limited availability of UWB trading systems make it impractical for wearable systems. Finally, the Wi-Fi enables direct internet connection and large data transfer with minimal latency, but due to the high-power consumption and its complex settings it is unprofitable for long-term monitoring systems where longer battery life is required.

Lastly, LoRa is the physical layer, or the wireless modulation utilised to create the long-range communication link. Many legacy wireless systems use Frequency Shifting Keying (FSK) modulation as the physical layer because it is a very efficient modulation for achieving low power. LoRa is based on chirp spread spectrum modulation, which maintains the same low power characteristics as FSK modulation but significantly increases the communication range. Chirp spread spectrum has been used in military and space communication for decades due to the long communication distances that can be achieved and robustness to interference, but LoRa is the first low-cost implementation for commercial usage. LoRaWAN defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link. The protocol and network architecture have the most influence in determining the battery lifetime of a node, the network capacity, the quality of service, the security, and the variety of applications served by the network. Many existing deployed networks utilise a mesh network architecture. In a mesh network, the individual end-nodes forward the information of other nodes to increase the communication range and cell size of the network. While this increases the range, it also adds complexity, reduces network capacity, and reduces battery lifetime as nodes receive and forward information from other nodes that is likely irrelevant for them. Long range star architecture makes the most sense for preserving battery lifetime when long-range connectivity can be achieved. LoRaWAN defines ten channels, eight of which are multi data rate from 250bps to 5.5 kbps, a single high data rate LoRa channel at 11kbps, and a single FSK channel at 50kbps. The maximum output power allowed by ETSI in Europe is +14dBM, with the exception of the G3 band which allows +27dBm. There are duty cycle restrictions under ETSI but no max transmission or channel dwell time limitations.

Wireless technology	**Frequency band**	**Range**	**Data Rate**	**Power consumption**	**Max supported nodes**	**Supported network topologies**	**Security**
RFID	13.56 MHz 860-960 MHz	0-3 m	640 kbps	200 mW	1 at a time	P2P (passive)	N/A
Bluetooth	2.4-2.5 GHz	1-100 m	1-3 Mbps	2.5-100 mW	1 master + 7 slaves	P2P, star	56-125 bit key
BLE	2.4-2.5 GHz	10-100 m	1 Mbps	10 mW	1 master + 7 slaves	P2P, star	128-bit AES
ZigBee	2.4-2.5 GHz	10-100 m	250 kbps	35 mW	65533	P2P, star, tree and mesh	128-bit AES
Wi-Fi	2.4-2.5 GHz	150-200 m	54 Mbps	1 W	255	P2P, star	WEP, WPA, WPA2

Wireless technology	Frequency band	Range	Data Rate	Power consumption	Max supported nodes	Supported network topologies	Security
UWB	3.1-10.6 GHz	3-10 m	53-480 Mbps	250 mW	1 master + 7 slaves	P2P, star	
ANT	2.4-2.5 GHz	30 m	20-60 Kbps	0.01-1 mW	65533 in one channel	P2P, star, tree and mesh	64-bit key
MICS	402-405 MHz	2 m	200-800 Kbps	25 μW		P2P, star	
IrDA	38 kHz	10 cm	1 Gbps		1 at a time	P2P	
NFC	13.56 MHz	5 cm	424 Kbps	15 mW	1 at a time	P2P	AES
LORA	867-869 MHz	5 km[15]	0.25-50 Kbps	25 mW	62000[16]	star	AES

Table 3. Well known communication protocols and their characteristics

2.4 Security, Privacy and Reliability of Wearable Systems

Most wearable devices and their applications are wireless. As a consequence, security and privacy issues constitute major challenges. Because of the immediate involvement of people, concerns about protecting privacy must be addressed.

Security is one of the most important aspects of wearable systems. Mainly, it concerns the establishment and the implementation of protective means in order to ensure the system will not be violated by hostile or malicious acts. In general, security measures should be established to govern the overall operation of the system. A well-defined user hierarchy combined with strong authentication measures can prevent security breaches. Such measures should include control of access mechanisms so that only authorised users can have access to the data. Data routing may also be implemented as a security measure. Attackers can cause routing inconsistencies resulting in incorrect destination

[15] Depends on terrain.

[16] Depends on the gateway specifications

and recipients. Wireless networks are very prone to intrusion, so intrusion detection and prevention techniques are essential to prevent such attacks. Due to the sensitive nature of the data as they concern users, additional measures are required such as data encryption and continuous network monitoring. Continuous monitoring may not be a cost-effective measure but encrypting and creating secure user groups can be both cost-effective and protective.

The privacy of wearable systems is also a major concern in wireless sensor networks. Users' data are personal and their transmission over wireless media can pose a serious threat to users' privacy. Therefore, measures such as encrypting communications over wireless networks are necessary to assure user privacy.

3. Wearable Platform, Interfaces and Protocols

3.1 Wearable Platform

The wearable device developed and used within the project constitutes the basis of the Comfort and Wellbeing Module as the whole system operation depends on the data produced by this device. It is equipped with appropriate sensors that measure the user's physiological parameters, activity level and environmental conditions. The wearable is an easy-to-use, user-friendly device which is placed on the user's wrist in the form of a watch. The optical sensor used, records Photoplethysmography (PPG), a non-invasive optical technique for unobtrusive monitoring of changes in the blood flow dynamics and assesses the physiological parameter of Heart Rate (HR), which enables the control of the user's physical condition. Utilising the acceleration data, activity classification is performed, through which the Metabolic Rate (MR) value is calculated. The recorded environmental parameters involve Air Temperature (T) and 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 transmits the measurements wirelessly, allowing data flow towards the backend where it can be further processed and then, made available for visualisation. If there is a lack of an available network connection while the device is operating, the data is stored locally. As soon as the connection is re-established, the communication mechanism with the backend structure is activated and transmits the stored data along with the current ones.

There are two hardware versions entailed which incorporate different wireless communication protocols, optical sensor hubs and microcontrollers boards while the environmental sensor hub is the same at both versions. In addition, both hardware versions integrate an ultra-low power, 3-DOF MEMS accelerometer sensor with measurement ranges of ±2g, ±4g, and ±8g.

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The first hardware design implementation incorporates the ESP-WROOM-32 module by Espressif[17]. It is about a low-cost, low-power system on a microcontroller chip with integrated Wi-Fi and dual-mode Bluetooth. The ESP32 deploys a Tensilica Xtensa dual-core 32-bit LX6 microprocessor into which the device's software is executed. Regarding the optical sensor, the device integrates the MAX30105 breakout sensor board by Pimoroni[18]. It is a high-sensitivity optical sensor able to continuously obtain the PPG signal. The corresponding printed circuit board of this device is depicted in Figure 1.

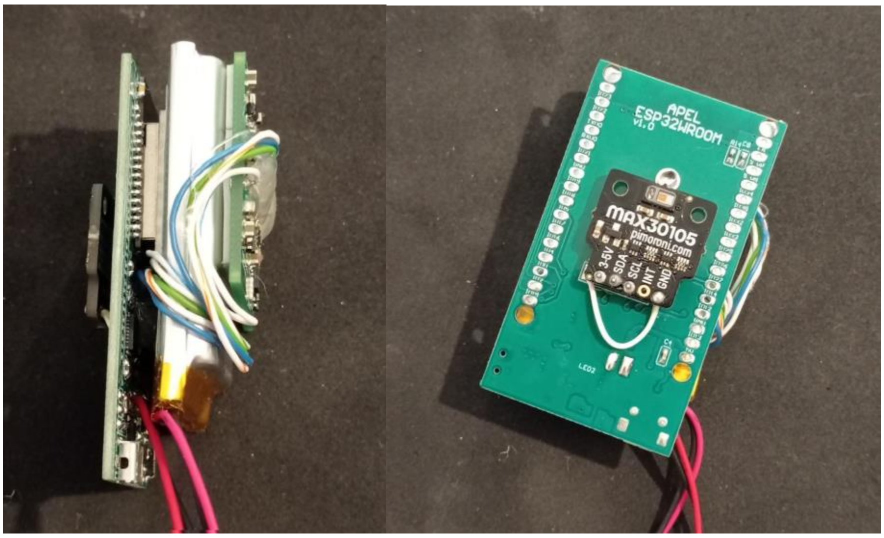

Figure 1. Printed Circuit Board of the wearable device - version 1

Specifically, the wearable embedded device is based on the ESP32 module by Espressif. ESP32 is a highly integrated solution for WiFi and Bluetooth IoT applications which integrates an antenna switch, RF balun, power amplifier, filters, and power management modules. The device is powered by a Li-Po 1600 mAh 3,7 V battery, which provides sufficient battery autonomy for 72hours in continuous operation mode. The sensing capabilities include a low power photoplethysmography (PPG) sensor, an accelerometer, and environmental sensors. The PPG signal is collected by the MAX30105 sensor manufactured by Maxim Integrated. It is an optical sensor providing high sensitivity which

[17] https://www.espressif.com/en/products/modules/esp32

[18] https://grobotronics.com/pimoroni-heart-rate-oximeter-smoke-sensor-max30105.html?sl=en

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comprises two light sources, one red with wavelength of 660 nm and one infrared with wavelength of 880nm, and a photodetector which is located horizontally at the underside of the printed circuit board. Dedicated algorithm for manipulating the PPG signals detected from the photosensitive detector, derives the desired physiological parameter of HR. Analog Device's ADXL362 is utilized as an ultra-low power, 3-DOF MEMS accelerometer sensor[19]. Moreover, a MR value is calculated by classifying the acceleration data into activity levels.

The second hardware design implementation of the device is based on the STM32WL55 module which integrates an Arm Cortex-M4, Arm Cortex-M0 and the LPWAN radio. The sensor board incorporates the max86141 chip, which is the AFE (Analog Front End) controlling the leds and acquires the raw PPG data from the photodiodes. In addition, the max32664 chip is integrated which includes the algorithms responsible for the extraction of physiological parameters from the raw PPG signals. Finally, the sensor board comprises the KX122, an accelerometer used by max32664 to identify motion and filter the raw PPG signal. The corresponding printed circuit board of this device is depicted in Figure 2.

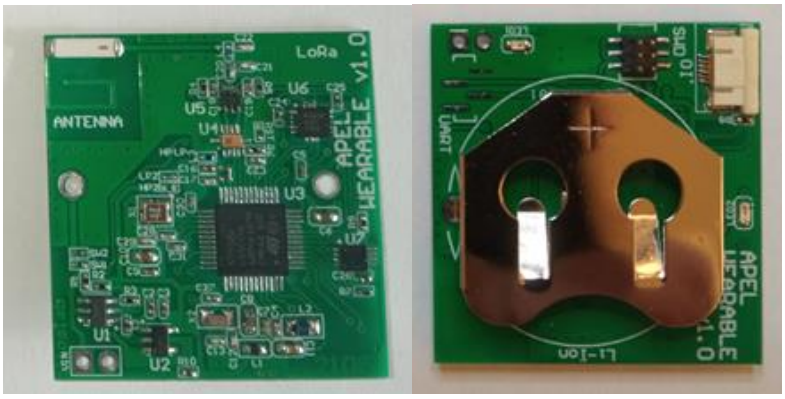

Figure 2. Printed Circuit Board of the wearable device - version 2

Finally, in both designs, the environmental conditions are recorded by the environmental sensor board which includes the Air Temperature (T), Humidity (H), Atmospheric Pressure

[19] https://www.analog.com/en/products/adxl362.html

(P), Noise Level (N), Luminosity Level (L), Equivalent Carbon Dioxide Concentration (eCO_2) and the Total Volatile Organic Compounds (TVOCs). It has a size of 30 mm x 30 mm and in order to operate it needs a power supply of 2V to 5.5V. Specifically, the environmental sensor board includes:

- Bosch BME280 MEMS sensor for the concentration of ambient T, H and P
- SCioSense CCS811 sensor responsible for measuring the TVOC and eCO_2
- AMS TSL2591 sensor for measuring indoor brightness
- SiSonic's SPW2430 sensor for measuring environmental noise

3.1.1 System Specifications

Table 4 and Table 5 depict the functional and non-functional specifications of both versions of the wearable device.

a/a	Operating Specifications	Description	State
1	Acquiring data from the wrist wearable device	The recording biosignal is the PPG, from which the HR value is calculated. Acceleration and environmental data are gathered as well	The HR value is calculated from the PPG. A MR value is estimated by the acceleration data. Finally, the environmental conditions recorded are Air Temperature (T), Relative Humidity (H), Atmospheric Pressure (P), Noise Level (N), Luminosity Level (L), Equivalent Carbon Dioxide Concentration (eCo_2) and Total Volatile

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			Organic Compounds (TVOCs)
2	Local data storage on the device	Local data storage offers the possibility of sending data at a later stage in the case of an imminent failure to transmit on the first attempt	Local storage has the capability of successfully storing up to 20 minutes of data. If a communication failure occurs, the data are available for later transmission when the problem is resolved
3	Operation of the device outside of the network range	The principles for operating the device outside of the wireless network's range must be defined	See fulfilment of requirement a/a2
4	Data transmission frequency	The frequency of the data transmission must be selected, on the one hand, to ensure that no event of critical importance is lost and, on the other hand, to aid	The frequency of the data transmission has been set to 1 minute to ensure that no critical event is lost

		the optimization of energy consumption	

Table 4. Functional specifications of the wearable device

a/a	Non-Functional Specification	Description	State
1	Security and Privacy	Protection of any natural person with regards to the processing of personal data and the free flow of such data	The data are sent to the predefined back-end system and are not permanently stored on the device. The https protocol is used to transmit the data from the device to the back-end system
2	Confidentiality of the data, both during transmission and in storage and processing	The retention policy will take care of the anonymization and pseudonymization of the data in order to ensure the inability to identify any natural person with their personal data	At the device level, association of information with a natural person is not taking place

3	Integrity of the data	Unauthorised modification and accidental loss or destruction of data could have severe consequences for the data integrity specification	Maintenance is required regularly to prevent physical deterioration of the device
4	Ease of use	The design of the system should be user centric	Wearable, on wrist, non-intrusive device with dimensions: 66mm x 42mm
5	Maintainability	It is crucial to maintain a high level of effectiveness and efficiency of the device.	Maintenance is required at regular intervals.
6	Performance Efficiency	Performance in relation to the number of resources used under certain conditions.	72 hours of standalone operation

Table 5. Non-functional specifications of the wearable device

3.1.2 Wearable Device Software

HR measurement

Both versions of the device use the photoplethysmography method to extract the desired physiological parameters from the wrist. The PPG method is 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 artefacts that appear due to any type of movement of the user and impose noise on the signal. Stronger and more complex motion artefacts 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[20]. 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. 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[21], 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 specific measurement[22]. 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 formula (1):

$$HR = Fs * 60 / d \text{ bpm} \quad (1)$$

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.

[20]Shahid Ismail, Usman Akram, Imran Siddiqi. 2021. Heart rate tracking in photoplethysmography signals affected by motion artifacts: a review. EURASIP J. Adv. Signal Process. https://doi.org/10.1186/s13634-020-00714-2

[21]M. Raghu Ram, K. Venu Madhav, E. Hari Krishna, K. Nagarjuna Reddy, K. Ashoka Reddy. 2010. Adaptive reduction of motion artifacts from PPG signals using a synthetic noise reference signal. IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES). 315-319. 10.1109/IECBES.2010.5742252.

[22]Dwaipayan Biswas, Neide Simões-Capela, Chris Van Hoof, Nick Van Helleputte. 2019. Heart Rate Estimation From Wrist-Worn Photoplethysmography: A Review. IEEE Sensors Journal. 19(16):6560-6570. 10.1109/JSEN.2019.2914166

Met value

With the aim to classify the movement in categories as dictated by the ASHRAE American Standard depicted in Table 6, 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 i n 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 (2):

$$Acc = \sqrt{Acc_x + Acc_y + Acc_z} \quad (2)$$

and then the double integral is calculated. In this application 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.

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. moderate effort home exercise)	350-550	2
High Activity (i.e. vigorous exercise)	>550	2.5

Table 6. Activity categorization with corresponding met values (ASHRAE standard)

Environmental Data

The values of the environmental parameters are recorded directly by the environmental sensors which are properly mounted on the wearable device so there is no further processing.

3.1.3 Measurements Validation

HR physiological parameter

The validation of the HR measurements of the device was carried out in the form of experiments conducted in the laboratory during which the estimated values were compared with their respective reference values. As a reference device for the HR values, the Berry's finger pulse oximeter was utilised[23]. The experiments were divided into two different categories of activity: sedentary state and moderate movement which were selected on the basis of the Borg scale[24], that corresponds to different levels of exercise to three states of movement: sedentary, moderate and intense movement. The method used to compare the estimated and reference values was the mean absolute error, a typical method for comparing quantitative units, which calculates the average deviation between the estimated and the reference values. It is clear that moderate movement leads to a greater average error in terms of heart rate values when compared to the sedentary state (rest), which can lead to unreliable measurements. On the contrary, at rest, the good performance and reliability of the wrist device is confirmed, as the estimated values achieve a low average error. Small discrepancies between the measurements of the devices used in the experiments are acceptable due to the different anatomical site of application for each device.

Environmental Data

With regard to the validation of measurements for the environmental parameters: temperature, air humidity and atmospheric pressure, a calibrated commercial device was chosen as the reference device and the comparison did not show any considerable deviation. The validation of noise level and brightness measurements was done through corresponding certified smartphone applications. Finally, the validation of the measurements for Equivalent Carbon Dioxide Concentration (eCO_2) and Total Volatile

[23] https://berrymedical.en.made-in-china.com/product/NZfahoXHlMVI/China-Good-Sales-and-Quality-Portable-Classy-Medical-Supply-Wrist-Pulse-Oximeter-Bm2000d.html

[24] https://www.cdc.gov/physicalactivity/basics/measuring/exertion.htm

Organic Compounds (TVOCs) was done through meteorological stations of the Greek National Meteorological Service.

3.2 Graphical User Interfaces and Protocols

3.2.1 Graphical User Interfaces

In the literature, it is often referred to as "user interface engineering" and it includes the designing of websites, applications, communication devices based on user experience and interaction. The aim of the design is to improve the interaction with the device by making the use of the device more efficient and simpler, following a user-centred design. In this process, the proper graphical representation plays a very important role, implemented without unnecessary information or icons, which do not facilitate the usability of the application.

For the graphical representation of a system to succeed, the purpose that the visualisation will satisfy needs to be understood to the maximum extent possible. For this to happen, a series of steps must be followed, depending on the specifics of the project. These are:

- Collection of functional requirements: A list is created according to the needs of the user or the system, so that the exact purpose of the application is clearly stated and understood.
- User analysis: Study of the potential users of the system. This can be done mainly through an interview.
- Information Organisation: Information is usually organised in a tree-like form and refers to the hierarchy of pages when it comes to a website or the display of information when it comes to a mobile phone application.
- Prototypes: Development of indicative visual representations of the application in paper or electronic form, so that it is easier to study.
- Study of usability: The usability of the application is evaluated from the very first stages of development, in order to avoid changes when the implementation is well

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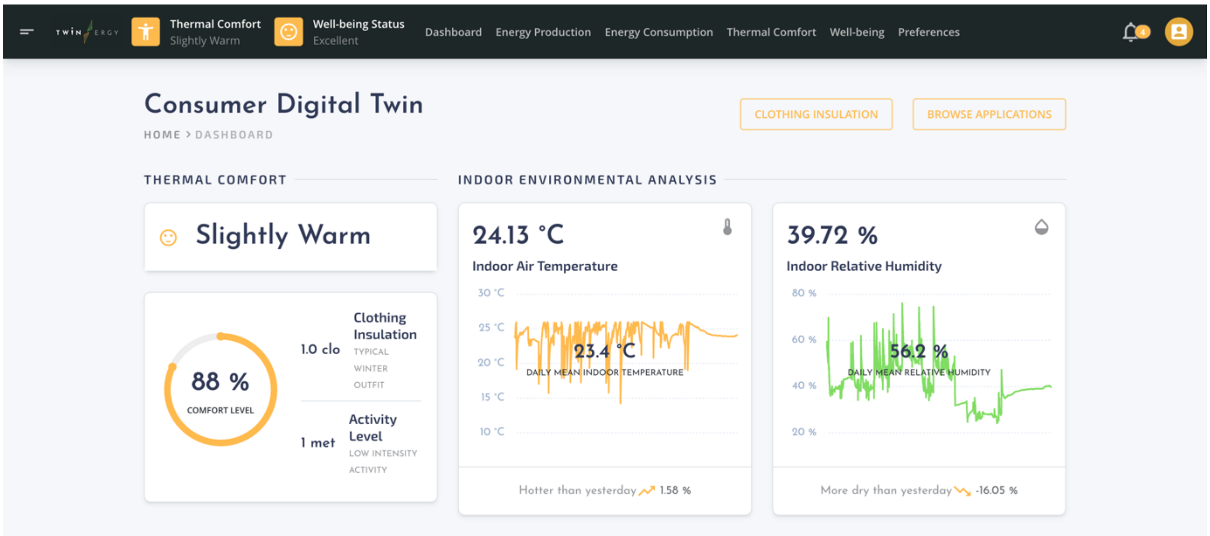
advanced, enabling as such better management of the total time needed for development. The evaluation is done in various ways, such as the use of the application by users without previous experience, or a heuristic evaluation, through which usability problems are identified.

- Usability check: Study of the interface, by real users, who report their thoughts and opinions during the test.
- Graphical interface design: It results from the observations that emerged during the development, considering the suggestions and comments of the users. Usually, the user and the app designer are involved in this process at the same time. Alternatively, it is possible for the procedure to be carried out by a single person provided that he can remain unbiased for both roles.

The wearable device of the comfort and wellbeing module does not incorporate a display through which the user can access layout or informational interfaces. The user's interaction with the system is done through an application on either web or mobile phone, as Figure 3. The application is designed according to the basic principles of human-machine interaction, while the graphical user interface is designed with a minimum colour palette. The application acts as a communication interface between the end user and the collecting services thus hosting POST and GET endpoints in order to interact with the cloud infrastructure.



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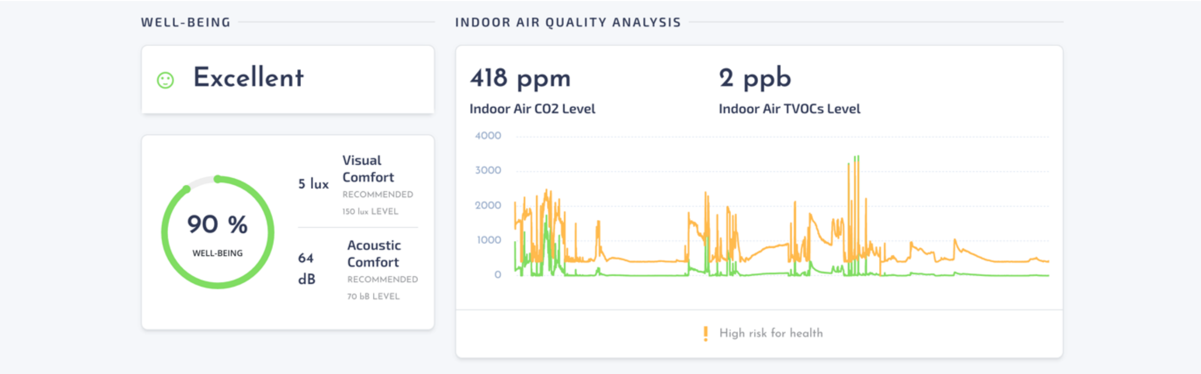

Figure 3. Graphical User Interface

3.2.2 Protocols

The privacy of wearable systems is a major concern in wireless sensor networks. Users' data are personal and their transmission over wireless media can pose a serious threat to users' privacy. The wearable device implements the HTTPS protocol to securely send the data via WiFi to the backend server. The payload's parameters are described in Table 7, while the form of the payload is as follows:

HR | AL | MET | TEMPERATURE | PRESSURE |HUMIDITY | LUX | eCO2 | TVOCs | ACOUSTIC

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.
eCO2	Equivalent Carbon Dioxide Concentration	ppm.
TVOCs	Total Volatile Organic Compounds	ppb.
ACOUSTIC	Noise Level	dB.

Table 7. Description of parameters included in the payload

4/ Thermal Comfort and Well-Being Standards

4.1. ASHRAE-55 Standard - Thermal Comfort

4.1.1. Introduction

ASHRAE has issued "ASHRAE-55 Standard: Thermal Environmental Conditions for Human Occupancy" that establishes environmental conditions within an indoor space to achieve acceptable TC for a specified fraction of occupants. ASHRAE-55 is a widely acceptable Standard, adopted to assess the TC 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 in TC. Our research has been based on the ASHRAE-55 version, published in 2010, which combines the ASHRAE-55-2004 document, as well as ten (10) approved addenda.

4.1.2. Thermal Comfort

TC 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 TC level, the production of heat must be equal to heat loss. TC is affected by both physiological and psychological parameters. The quantification of psychological parameters is hard due to the subjectivity of individuals. Therefore, ASHRAE-55 assesses the TC 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 80% of their daily routine.

4.1.3. Factors affecting Thermal Comfort

As mentioned before, the thermal satisfaction level is a combination of psychological and physiological parameters, however, ASHRAE-55 considers only the second ones. From the ensemble of physiological parameters, ASHRAE-55 makes a further classification into primary factors that have a strong impact on the TC and non-primary factors that slightly affect the TC. More specifically, the Standard considers six (6) 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. In our research, we proposed a method to capture personal factors either directly from a wearable device or from a user-friendly web-interface.

TC cannot be assessed in the transient state. Stable state requires residency of an occupant for more than 15 min within a space. As a result, people recently exposed to outdoor environmental conditions may experience different TC, and the effect of that prior exposure can last up to one (1) hour. Furthermore, TC requires uniform exposure to primary factors across the body, such as a uniform exposure in radiation from radiant heating systems or devices.

4.1.3.1. Environmental Factors

According to ASHRAE-55 Standard, the assessment of TC requires four (4) Environmental Factors, as listed below.

a. **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.
b. **Relative Humidity**, defined as the average moisture level of the air that surrounds the occupant's body uniformly.

c. **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.
d. **Air Speed**, defined as the average speed of air that surrounds the occupant's body uniformly.

Note that the proposed methods to assess the TC may need more quantities that derive from the Environmental Factors listed above, such as the Operative Temperature results from the Air Temperature and Radiant Temperature.

4.1.3.2. Personal Factors

According to ASHRAE-55 Standard, the assessment of TC requires two (2) personal factors, as listed below, and furtherly

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

Clothing Insulation

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 can 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 insulation level of occupants are not feasible for the average residency, as it requires the installation of high complexity and expensive systems inside the apartment. Thus, ASHRAE-55 Standard has proposed methods to assume that value based on predefined common clothing ensembles, such as typical winter and summer outfits, and individual garments. Some specified Clothing Insulation values for typical ensembles are shown in Table 8. During

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the initialization process, an occupant can either choose a clothing ensemble process or choose a sum of individual garments.

Typical Outfit	Clothing Insulation
Trousers	
Trousers, short-sleeve shirt	0.57 clo.
Trousers, long-sleeve shirt	0.61 clo.
Trousers, long-sleeve shirt, suit jacket	0.96 clo.
Trousers, long-sleeve shirt, suit jacket, vest, T-shirt	1.14 clo.
Trousers, long-sleeve shirt, suit jacket, long-sleeve sweater, T-shirt	1.01 clo.
Trousers, long-sleeve shirt, suit jacket, long underwear bottoms	1.30 clo.
Skirts	
Knee-length skirt, short-sleeve shirt (sandals)	0.54 clo.
Knee-length skirt, long-sleeve shirt, full slip	0.67 clo.
Knee-length skirt, long-sleeve shirt, half-slip, long-sleeve sweater	1.10 clo.
Knee-length skirt, long-sleeve shirt, half-slip, suit jacket	1.04 clo.
Ankle-length skirt, long-sleeve shirt, suit jacket	1.10 clo.
Shorts	
Walking shorts, short-sleeve shirt	0.36 clo.
Long-sleeve coveralls, T-shirt	0.72 clo.
Overalls / Coveralls	

Typical Outfit	Clothing Insulation
Long-sleeve coveralls, T-shirt	0.72 clo.
Overalls, long-sleeve shirt, T-shirt	0.89 clo.
Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37 clo.
Athletic	
Sweatpants, long-sleeve sweatshirt	0.74 clo.
Sleepwear	
Long-sleeve pyjama tops, long pyjama trousers, short ¾ length robe	0.96 clo.

Table 8. Clothing Insulation Values for Typical Ensembles

The consumer can insert the Clothing Insulation (CI) through the Consumer's Digital Twin (CDT) GUI. A user-friendly front-end has been developed to increase the consumer's engagement rate with the CDT, and sequentially, updates the CI in regular intervals to optimise the TC assessment, as CI has a significant impact on the TC and it's hard to be measured automatically. The CI requires a two-step process from the consumer, as can be seen in Figure 4. First, the consumer must choose between four predefined (4) typical outfits, one for each season, summer outfit, winter outfit, spring outfit and autumn outfit. After the selection of a typical outfit, the consumer can adjust the garments of the predefined outfits to decrease or increase the insulation level as proposed by the typical outfits. More specifically, the consumer can update the settings of each typical outfit through a series of dropdown lists and submit changes to update the CI parameter of the PMV Method.

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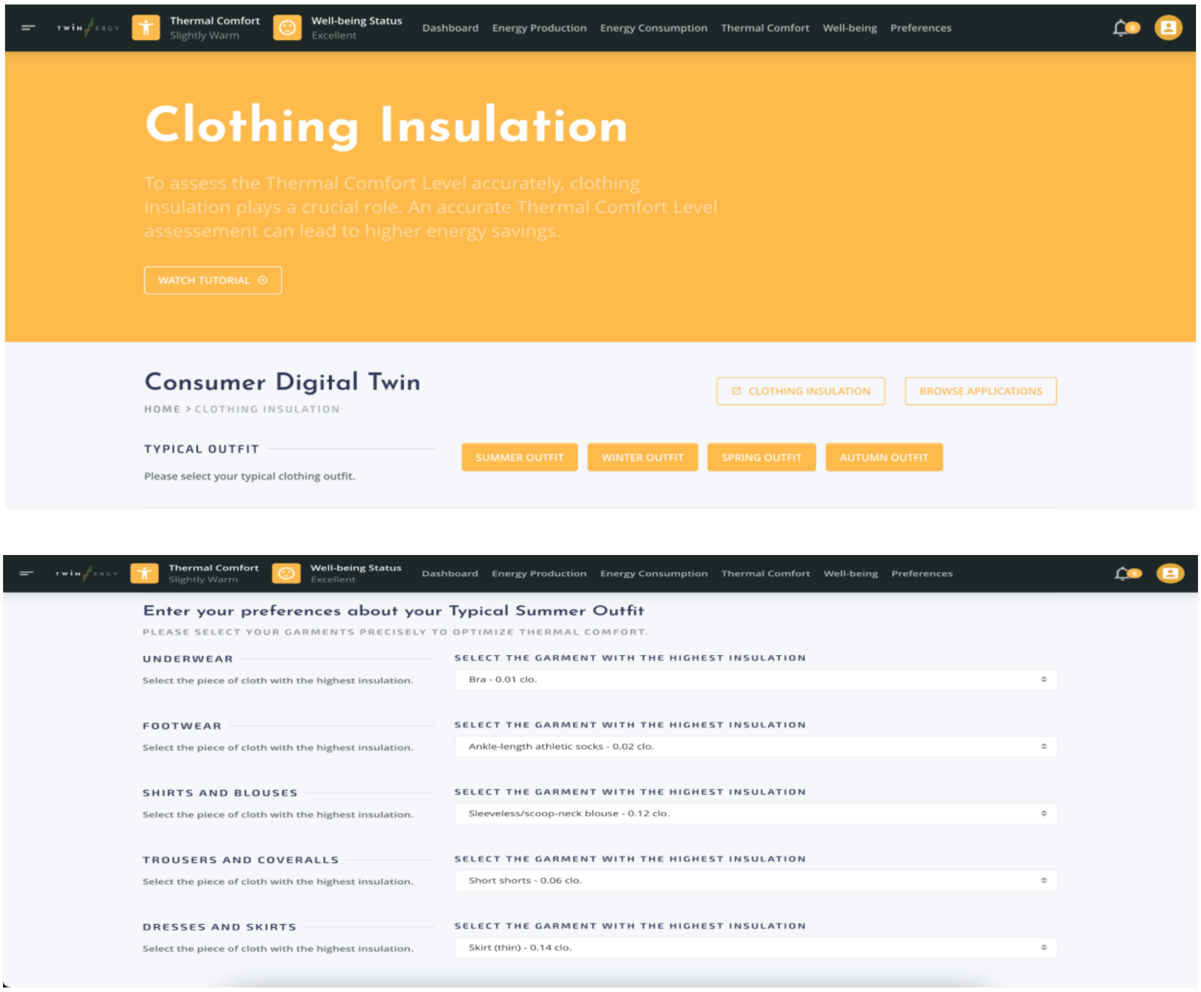

Figure 4. Clothing Insulation GUI

Metabolic Rate

The MR is a physiological measurement of metabolism during physical activity and can be expressed either in units of W/m^2 or met. Figure 5 lists some met values for specific indoor activities. The increase of MR leads to evaporation of sweat and hence to warm discomfort. As a result, PMV method cannot work properly in activities with time-averaged MR above 2.0 met. In general, the TC is intended to sedentary or near sedentary physical levels of a typical household or office.

Activity	Metabolic Rate	**Note that these MR**
Resting	0.7 - 1.2 (met)	

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Walking on Level Surface *	2.0 - 3.8 (met)	**values refer to the <u>skin surface area of an average adult</u> (DuBois area = 1.8 m²) and activities performed continuously.**
Office Activities	1.0 - 2.1 (met)	
Cooking	1.6 - 2.0 (met)	
House Cleaning	2.0 - 3.4 (met)	
Machine Work (Light)	1.8 - 2.4 (met)	

Figure 5. Metabolic Rate of various indoor activities and states

4.1.4. PMV Method

PMV Method proposes a stationary model to predict TC based on the theoretical basis of Fanger's Method. This model is the most used thermal sensation metric within indoor spaces. PMV Method evaluates the TC by employing an equation that combines quantitatively environmental and personal factors as referred in section 3.1.3. The prediction is an index value within the range of -3 (Cold) to +3 (Hot) 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; Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool and Cold, as shown in the Table 9.

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Table 9. ASHRAE-55-2010 7-points scale

The thermal satisfaction level is maximum when the index value of PMV converges to 0 (Neutral), and minimum when index value reaches the edge values of +3 (Hot) or -3 (Cold). The typical PMV index values of thermal satisfaction are within the range of -0.5 to +0.5.

As mentioned before, PMV employs a mathematical model to quantify the TC within an indoor space. However, a series of intermediate steps should be executed to transform the equation's variables into the appropriate units, calculate derivative quantities from the primary factors (variables), i.e., environmental and personal factors and calculate variables corresponding to the heat exchange between the body and the surrounding environment. In our approach, we have proposed a serial algorithm with four (4) discrete steps to calculate the PMV index value, as follows:

PMV Algorithm

Step 1: Collect and retrieve data acquired from wearable devices, sensors and data manually inserted by the occupant.

The data acquired from wearable devices, sensors and data manually inserted by the occupant are presented at the table below.

Factor	Units	Symbol	Source	A/M
Environmental Factor				
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

Table 10. Acquired parameters

Step 2. : Calculate the derivative quantities from the Environmental and Personal Factors.

Before the calculation, we should transform MR from met units to W/m^2 to be compatible with the PMV mathematical formula. In addition, the External Work (W) is usually small, and a common practice is to be assumed as 0 met.

$$M = M * 58 \quad (3)$$

Step 2.1: Calculate the variable t_{sk} - the Skin External Temperature

$$t_{sk} = 35.7 – 0.028 * (M - W) \quad (4)$$

Step 2.2: Calculate the variable F_{cl} - the Clothing Area Surface Factor

$$F_{cl} = 1.05 + 0.65 * I_{cl} \quad (5)$$

Step 2.3: Calculate the variable t_{cl} - the Clothing Surface Temperature

$$(t_{sk} - t_{cl}) / I_{cl} = 3.96 * 10^{-8} * f_{cl} * [(t_{cl} + 273) * 4 - (t_r + 273) * 4] + f_{cl} * h_c * (t_{cl} - t_a) \quad (6)$$

Step 2.4: Calculate the variable h_c - the Convection Coefficient

$$h_c = 12.1 * A_v^{½} \quad (7)$$

Step 2.5: Calculate the variable p_a - the Partial Vapour Pressure

$$p_a = (t_a / 100) * 0.1333 * e^{(18.6686 - 4030.183 / (ta + 235))} \quad (8)$$

Step 2.6: Calculate the variable t_r - the Mean Radiant Temperature

$$t_r = t_g + 2.42 * A_v * (t_a - t_g) \quad (9)$$

Step 3. : Calculate the variables corresponding to the heat exchange between the body and the surrounding environment.

Step 3.1: Calculate the variable H - the Sensitive Heat Losses

$$H = 3.96 * 10^{-8} * f_{cl} * [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} * h_c * (t_{cl} - t_a) \quad (10)$$

Step 3.2: Calculate the variable E_c - the Heat Exchange by Evaporation on the Skin

$$Ec = 3.05 * 10^{-3} * [5733 – 6.99 * (M-W) - p_a] - 0.42 * [(M-W) - 58.15] \quad (11)$$

Step 3.3: Calculate the variable C_{res} - Heat Exchange by Convection in Breathing

$$Cres = 0.0014 * M * (34 - t_a) \quad (12)$$

Step 3.4: Calculate the variable E_{res} - the Evaporative Heat Exchange in Breathing

$$Eres = 1,7 * 10^{-5} * M * (5867 - p_a) \quad (13)$$

Step 4. : Apply the values of variables calculated at the previous steps on the PMV mathematical formula.

The PMV index is calculated from the equation (14).

$$PMV = (0,303e^{2,1*M} + 0,028) * [(M\text{-}W)\text{-} H - Ec - Cres - Eres] \quad (14)$$

Additionally for validation purposes, we have developed the web-based application "PMV Calculator'', as depicted in Figure 6. It consists of a two-step form wizard and indexes the PMV value when environmental and personal factors are inserted.

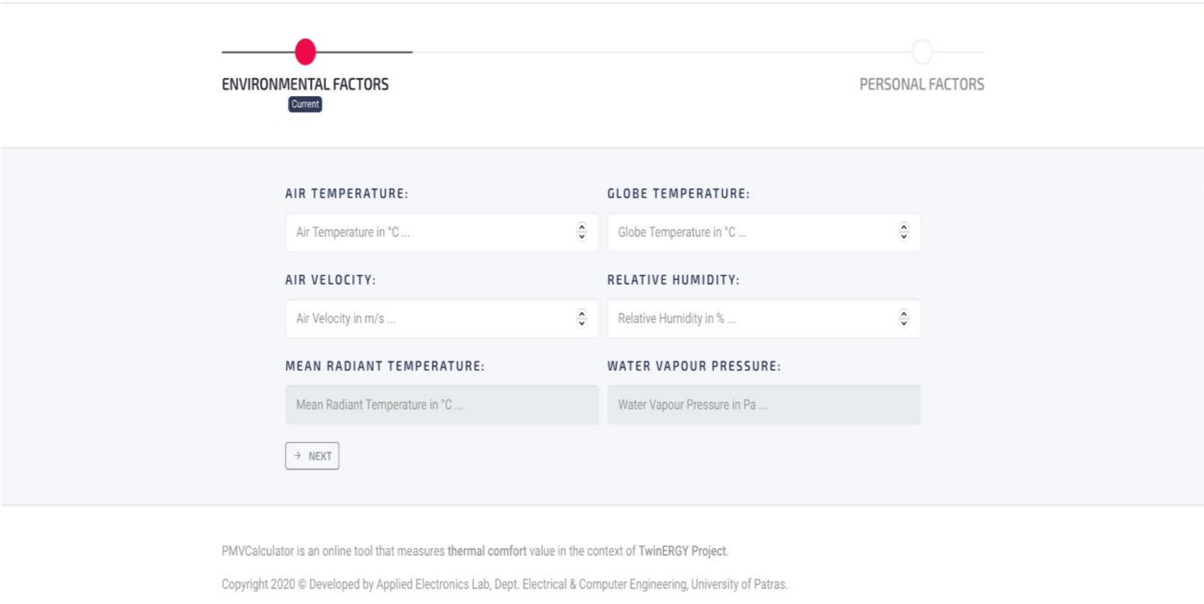

Figure 6. Environmental factors

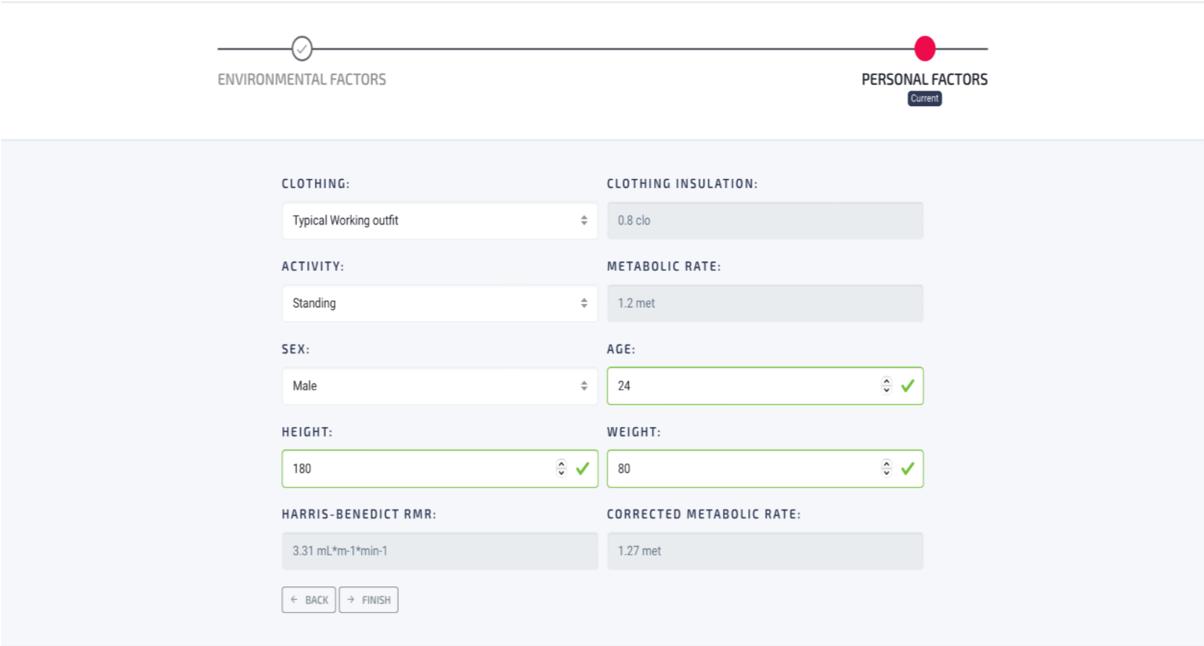

Figure 7. Personal factors

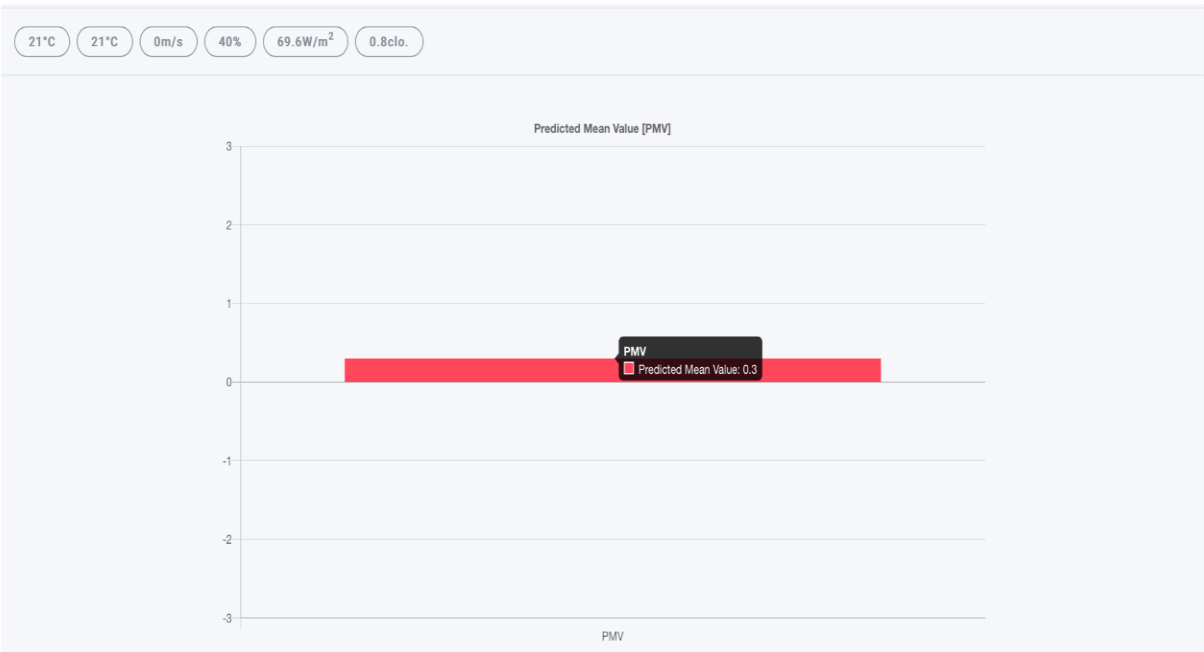

Figure 8. PMV Calculator

4.1.5. PPD

PPD is an index that establishes a quantitative prediction of the percentage of the thermally dissatisfied occupants determined from PMV. It is more reliable than PMV, as the individual votes show scatter due to personal factors. More specifically, in a neutral thermal environment, there will be a percentage of occupants that may feel cold or warm, instead of the neutral sensation predicted by the PMV method and vice versa. That fragment of occupants is calculated from equation (15).

$$PPD = 100 - 95 * exp(-0.03353*PMV^4 - 0.2179*PMV^2) \quad (15)$$

As the PMV index reaches extreme states, i.e., the "Cold" and "Hot" TC level, the dissatisfaction rate increases exponentially. The lowest dissatisfaction rate is observed near the Neutral state, i.e., for PMV index values around zero. Table XI presents the PPD for some typical PMV index values.

PMV	PPD
0	approx. 5 % of occupants dissatisfied
-0.25 **OR** 0.25	approx. 6.30 % of occupants dissatisfied
-0.50 **OR** 0.50	approx. 10.00 % of occupants dissatisfied
-1.00 **OR** 1.00	approx. 26.30 % of occupants dissatisfied
-1.50 **OR** 1.50	approx. 51.10 % of occupants dissatisfied
-2.00 **OR** 2.00	approx. 76.90 % of occupants dissatisfied
-2.50 **OR** 2.50	approx. 93.50 % of occupants dissatisfied

Table 11. PPD for some typical PMV index values

4.2. Standard Guidelines and Regulations for Indoor Air Quality

Field studies have pointed out that CO_2 and TVOCs are the most representative and independent environmental parameters which can be used as an evaluation index of Indoor Air Quality in indoor environments. Therefore, our research focuses on the measurement of those two air pollutants. To align with the guidelines and regulations of Standards and health agencies, we adopted the 'ASHRAE-62 Standard' to classify the CO_2 levels and 'WHO: Indoor Air Quality for Europe' to classify the TVOCs levels.

Indoor air quality Standards are mostly implicit, based on guidelines created by the CDC, ASHRAE and OSHA for maintaining clean air in indoor environments. In the scope of our research, we followed the guidelines of ASHRAE-62 Standard for the acceptable CO_2 levels in domiciles and WHO guidelines for acceptable TVOCs levels. Table 12 lists the CO_2 concentration levels as they are specified by the ASHRAE-62 Standard, while Table 13 the TVOCs levels defined by WHO.

Recommendation	Health Symptoms	CO_2 [ppm]
Target Value	-	<1000
Warning	Complaints and Minor Health Symptoms	600 - 1000
Warning	Fatigue and Headaches	500 -3200
Warning	Release of Calcium from Bones	>3500
ASHRAE-62 Standard		

Table 12. ASHRAE-62 Standard - CO_2

Level	Recommendation	TVOCs [μg/m^3]
-	Greatly Increased (Not Acceptable)	>3000
L4	Significantly Increased (Only Temporary Exposure)	1000 - 3000
L3	Significantly Increased (Harmless)	500 - 1000

Twinergy has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 957736

L2	Average (Harmless)	250 - 500
L1	Target Value	-
World Health Organisation (WHO)		

Table 13. WHO – TVOCs

5/ Conclusions

Thermal sensation (TS) and Thermal Comfort (TC) relate to the living environments and the life of the occupants. TC, which expresses the personalized thermal satisfaction associated with the thermal environmental conditions, adheres to an ideal thermal condition and the corresponding tolerance limits which the occupant remains comfortable, while well-being status is associated with the quality of indoor air in terms of pollutants. Continuously determining occupants' TC and wellbeing 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. It is indispensable to enable occupants to depict their own personalised tolerance limits while continuously assessing TC in an automatic manner.

The comfort / well-being module, as described in this deliverable, provides the unobtrusive means to accurately determine according to existing standards the personalised TC level and / wellbeing status of the occupants, thus making them predictable energy wise and allow pertinent optimal energy demand management while preserving the desirable tolerance limits.

Annexes

A. Metabolic Rate - Annex

Activity	Metabolic Rate
Sleeping	0.8 met.
Seated relaxed	1.0 met.
Standing at rest	1.2 met.
Sedentary activity (office, dwelling, school, laboratory)	1.2 met.
Car driving	1.4 met.
Graphic profession - Book Binder	1.5 met.
Standing, light activity (shopping, laboratory, light industry)	1.6 met.
Teacher	1.6 met.
Domestic work -shaving, washing and dressing	1.7 met.
Walking on the level, 2 km/h	1.9 met.
Standing, medium activity (shop assistant, domestic work)	2.0 met.
Building industry - Bricklaying (Block of 15.3 kg)	2.2 met.
Washing dishes standing	2.5 met.
Domestic work - raking leaves on the lawn	2.9 met.

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Activity	Metabolic Rate
Domestic work - washing by hand and ironing (120-220 W)	2.9 met.
Iron and steel - ramming the mold with a pneumatic hammer	3.0 met.
Building industry - forming the mold	3.1 met.
Walking on the level, 5 km/h	3.4 met.
Forestry - cutting across the grain with a one-man power saw	3.5 met.
Volleyball, Bicycling	4.0 met.
Callisthenics	4.5 met.
Building industry - loading a wheelbarrow with stones and mortar	4.7 met.
Golf, Softball	5.0 met.
Gymnastics	5.5 met.
Aerobic Dancing, Swimming	6.0 met.
Sports - Ice skating, 18 km/h, Bicycling (20 km/h)	6.2 met.
Agriculture - digging with a spade (24 lifts/min.)	6.5 met.
Skiing on level, Backpacking, Skating ice or roller, Basketball, Tennis	7.0 met.
Handball, Hockey, Racquetball, Cross County Skiing, Soccer	8.0 met.
Running 12 min/mile, Forestry - working with an axe	8.5 met.
Sports - Running in 15 km/h	9.5 met.