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The Complexity of Simple Goals: Case Study of a User-Centred Thermoregulation System for Smart Living and Optimal Energy Use

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Abstract: There are currently several systems for home automation and energy management available on the market. These systems are intended to reduce the use of energy, while ensuring optimal and customizable comfort conditions. The advances in technology (Internet of Things, sensors, cloud computing, data processing and thermal modelling) and in the design of interfaces should facilitate the adoption of convenient behaviours by final users, thereby producing more sustainable use of energy at home. Conversely, the effectiveness and efficiency of smart home systems for thermo-regulation is a complex activity, requiring the collaboration of multiple stakeholders and experts. In this paper, the authors report a case study about the design of a system for thermal regulation at home developed in a multidisciplinary research team for research and industrial purposes. The paper reports results including: a discussion on a number of issues involved in the design of smart home solutions for sustainability and on the importance of developing an integrated approach to their design; the needs analysis of users and of their functional requirements based on investigation with residents and profiling; final remarks about the role of User Experience Design methods and tools in the development of smart home solutions, understood as socio-technical systems.

Keywords: design for sustainability; alternative design models and strategies; user experience design; user centred design; energy management systems for home; home automation

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1. Introduction: Motivation and Research Goals

The evolution of technologies and of design approaches enables the creation of systems for home automation [1] and smart-home solutions [2–5] aimed at optimization of the comfort of residents and at the affordable use of resources and energy. Home automation systems can be created for a variety of different applications, aims and needs such as independent living, safety, wellbeing and health care.

The advances in this realm rely on the contributions provided by scholars, researchers and industries that operate in diverse application fields. They include different domains of Engineering (Electronics, Computer Sciences, System Automation, Energy, Artificial Intelligence and Machine learning) and different branches of design: Design for Experience (UX Design) and User centred Design to investigate the needs and behaviours of final users; Interaction Design to develop interfaces and functionalities; Service Design.

Instead, it is now recognized that the creation of effective, feasible and desirable systems for sustainability through automation at home still faces several challenges. It calls for further experimentation and research in different fields, including technologies (Information and Communication Technologies, Internet of Things, sensor-systems, technical plants and facilities) [3,4]; human factors (behaviours, needs, requirements) [6,7]; management and governance (business models, organization between stakeholders and partners,) [7].

With this paper, the authors intend to make a contribution to the development of knowledge to exploit smart home potentials in favour of comfort and sustainability. The case study herein reported refers to a project aimed at developing a system for thermal regulation at home capable of ascertaining user needs and of reducing energy use by combining technical solutions and design strategies. The reported case study is an example of successful cooperation between academic scholars and industries, in a multi-disciplinary environment. In such a context, designers, with expertise in Interaction Design and Design for Experience, acted as catalysers in the design process, investigating the needs and attitudes of final users and service providers as well as generating and envisioning design proposals with a view to increasing the efficiency and effectiveness of the collaboration, orienting efforts towards solutions capable of perceiving the needs, expectations and requirements of the stakeholders and partners of the system, including final users and service providers. The final solution exploits the contribution of technical solutions (data gathering through sensors, thermal modelling of buildings and plants, optimization algorithms) and provides through an innovative user interface the means to encourage virtuous behaviours in final users by offering a control system tailored to different user profiles.

According to the authors, the reported case study is a meaningful example of the effectiveness of a design-driven approach in the development of systems for sustainability in domestic environments. The paper aims to discuss the state of the art of the solutions for home automation with respect to sustainability, showing that these areas still have unexploited potentials; it also reports the design approach adopted in the project, summarizing some of the outcomes. Overall, the paper intends to demonstrate the potentials of a holistic and multi-disciplinary design approach to the design of solutions for sustainability at home. The authors argue that technical innovation in domestic environments cannot be effectively implemented without a thorough understanding of the motivations, needs and requirements of all the human subjects and stakeholders involved in the service delivery and use. The collaboration of partners – industries, energy experts, researchers, technologists and designers – requires a strategy of management for the design process, in order to harmonize and orient the different contributions toward a common goal and designers can make an effective contribution, making efforts converge towards a solution that meets the requirements of end users.

In the following part of the document, the authors present an analysis of the state of the art of the field and a discussion about the complexity of developing effective smart home solutions for sustainability; they describe the main features of the case study and the results of the investigations conducted with final users. Finally, the paper presents a number of remarks about the design methodology adopted in the research and discusses certain criticalities concerning the development of sustainable solutions for home automation.

1.1. The Complexity of Smart Home Solutions

The development of smart home solutions is the focus of several pieces of research in a variety of disciplines. The scientific publications provide definitions of the topic – smart home and home automation – and map the potentials of automation with respect to sustainability. Articles report the technical advances supporting the development of innovative solutions [8,9], social concerns [4,10], also including safety, security, privacy, social and engineering issues and the criticalities that have emerged in the implementation and testing of solutions developed for different purposes [11]. Scholars point out the importance of approaching the smart homes design taking into account the needs and preferences of final users, developing knowledge about human factors through dedicated research and modelling [12,13]. The evolution of control interface modalities and the criticalities connected with their usability is also the subject of research [1]. Other works highlight the role played by system stakeholders aside from users, such as installers and technicians assigned to maintenance, in order to effectively exploit the potentials of technical solutions with respect to sustainability [14,15]. Furthermore, a number of recent papers summarize the state of the art of the research in the field, also outlining certain theoretical knowledge, including a discussion on definitions and principles [16].

The interest exhibited by the topic in the scientific literature relates to the potentials of automation with respect to the goals of energy use reduction and the improvement of wellbeing. Among others, Marikyan et al. [16] provide a review of the state of the art, illustrating the potentials of technologies for homecare and for the independent living of ageing persons. These authors highlight the importance of Information and Communication Technologies in providing systems that anticipate and correspond to user needs in a flexible and sustainable manner. They underline how the cost reduction of technological components that support the implementation of innovative solutions for smart living at home is a factor designed to facilitate the creation of market and research interest for the development of accessible systems. Furthermore, these authors also report different approaches in the implementation of smart home solutions, also including control paradigms. They also refer to a number of critical issues that reduce the acceptance and adoption of smart-home solutions by users, including cognitive barriers, a lack of knowledge and trust, low perception of value and scarce evaluation of novelty. Other issues include difficulties in obtaining actual economical convenience and understanding of the service-conditions that provide convenience.

Fabi and Spiglianti [12] point out that the compliance of house inhabitants with respect to the expected behaviours, as predicted and described in the design of thermal facilities, is an essential condition for the effective implementation of solutions aimed at increasing the efficient use of energy at home. As human behaviours are variable and change over time, energy management systems should be designed to embrace user needs and to ensure dynamic adaptation and optimization with respect to evolving scenarios of use. The authors also recognize three principles for thermal regulation systems: (i) identifying and eliminating energy wastes; (ii) using energy only in the amount, at the place and at the time it is needed; (iii) implementing the right control, allowing variability of functions in time and place.

Trabelsi and others [17] analysed and modelled the preferences of residents in order to design an intelligent scheduler for the use of electrical appliances at home, assuming that “sustainable behaviour change will only occur when the user is satisfied with experience.” Their research outlines the importance attributed by users to comfort as a relevant need which counterbalances cost saving; it also reports the variability of the notion of comfort.

Nilsson and others [18] investigated the impacts of home energy management systems and the availability of data on energy use. The research reports the effects of feedbacks on user behaviours and on consumptions and it illustrates the variability of attitudes of users. The need for cost reduction and the awareness of the consequences of behaviours on energy use are only partially effective in inducing changes and they seem to have scarce effects on the scheduling of the use of electrical facilities. The paper illustrates the complex tangle of factors involved in the adoption of smart home solutions, listing three main factors that should be taken into account in the development of sustainable systems. The first factor is lack of knowledge: information about consumptions is not enough if not supported by knowledge about economic, technical and environmental issues. The second is a lack of a sense of control: cooking, laundry, cleaning and so forth, are often considered as basic and indispensable activities at home and the feedback relating to energy use can induce stress and anxiety. The latter regards values and attitudes that impact on the willingness to adopt solutions that force behaviours.

Pillan [19,20] reports the results of an ethnographic investigation at home, revealing the potentials of technologies to produce desirable solutions for wellbeing in domestic spaces but also highlights the importance of considering local cultures and attitudes in the development of technology-based products and services in order to embrace specific values with respect to housing, living and lifestyles.

The literature review also demonstrates that the design of an interface for thermal control at home, capable of accomplishing usability, accessibility and desirability requirements, is not a straightforward task and it requires a dedicated investigation of contextual conditions and the preferences of users [21]. The perception of wellbeing is influenced by a number of factors such as environmental factors (climate, spatial organization), social factors (age, activities) and physiological factors (gender, age) [12]. In fact, the perceived comfort, even with respect to the thermal conditions, can be significantly affected by other factors aside from temperature such as the level of humidity in the air [14]. The ability to consider the complexity of human perception of comfort in the development of algorithms that control conditioning systems provides further contributions to the potential reduction on energy uses [5,22].

Overall, the contributions reported in the dedicated literature provide a map of potentials and criticalities of solutions based on IoTs (Internet of Things) and ICTs (Information and Communication Technologies) in the realm of smart home from the point of view of final users. They also highlight the importance of an integrated approach to the development of such systems in order to address all the complex factors.

Our preliminary investigation of smart-home solutions based on a literature review produced the results and the findings that we summarize below.

The evolution of technologies and sciences have enormous potentials with respect to the solution of the double and in some way contradictory, goal of reducing energy use while increasing the wellbeing of residents.

The minimization of energy use obviously depends on the efficiency of the facilities for heat generation and thermal conditioning and on the effective management of their conduction with respect to the variable external conditions and user requirements. Moreover, several other factors impact on the final consumption and should be considered to reduce the footprint of thermal regulation in domestic environment, such as the availability of:

- technical facilities for data collection, sharing and processing, the ability to produce a full description of the environmental thermal conditions, of the thermal state of buildings and plants and of user needs and behaviours;
- precise thermal modelling of buildings and plants, able to describe their thermal performances, to predict their dynamic responses to variations and to calculate the convenient set-ups (time and power);
- suitable control systems that allow the creation of optimal comfort conditions in houses and the minimization of energy use.

1.2. TEPORE – An Experimental and Research Case Study for Sustainable Thermo-Regulation at Home

The case study we report here is from a research project named TEPORE (TErmoregolazione Partecipata e Organizzata per il Residenziale Evoluto), funded by the Lombardy Region. The funding aims to promote the collaboration between local industries and scholars and the transfer of technology skills and design methodologies. The project involves several partners such as the academic research teams (Interaction Design, Computer Sciences, Electronics, Architecture) of Politecnico di Milano, companies offering services and systems in the field of energy management and a consultancy company (a spin-off of Politecnico)—Enersem—to perform systems analysis and dynamic modelling of the thermal behaviour of buildings for the civil and industrial sectors. The research activities were mainly conducted in 2018 and 2019. As final outcomes, they produced industrial solutions in terms of hardware and software products, innovative sensor devices and building solutions, models and algorithms to be employed in monitoring and control systems as well as control applications for final users: residents, energy managers and conditioning service providers.

TEPORE is therefore an example of an integrated design of a system that aims to provide sustainable technological innovation in the field of home automation. The authors of this paper have been involved in TEPORE as interaction and UX designers for the design driven development of the information architecture and interfaces of the two new control systems, one for the final user (residents of domestic context) and the other one for energy managers and building administrators. The two new control systems are based on real-time data collection (indoor and outdoor thermal conditions, set-up of facilities, status of plants), on advanced thermal modelling of buildings and technical plants and on prediction algorithms for automatic, semi-automatic and manual management. TEPORE prioritises the reduction of energy uses and the optimizing of the comfort of inhabitants.

The control systems are considered in TEPORE as key factors which impact on the market desirability of thermo-regulation solutions and on energy use. For these reasons, in the project, the development of the two control systems was design-driven: the definition of the needs of all the stakeholders of the system, including resident-users, service providers and system managers, was conducted as a preliminary activity in order to take into account human factors in the development of technical and physical facilities. For both projects, the authors adopted a design methodology coherent with the Interaction Design principles [10,23] and based on preliminary research, scenario building, design of information architecture and graphical user interfaces, prototyping, testing and refinements. Research with residents and stakeholders provided knowledge about the real behaviours, needs and expectations of inhabitants, together with the investigation of goals, priorities and organization service providers involved in the energy delivery and management.

Our approach can be summarised in the following conceptual representation of the design problem for the development of smart home systems (Figure 1).

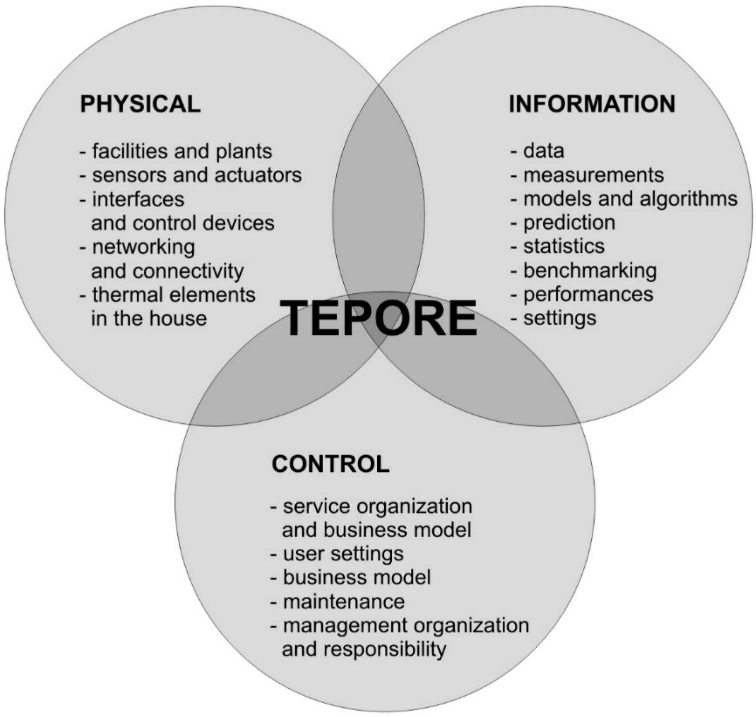


Figure 1. A conceptual representation of the design problem in TEPORE.

We classify thermal regulation systems as complex solutions, implying three different design dimensions: the physical domain, concerning material and digital solutions; the domain of information, including data generation, collection and post-processing based on modelling and on control algorithms; the domain of control and organization, supporting the activities performed by all the stakeholders of the systems - from users to service providers - and allowing information query, policy definition, system set-ups and decision making.

As reported in Figure 1, the physical domain includes technical solutions for the dynamic measurement of thermal conditions in public, semi-public and private spaces (sensors) and for the actuation of fulfilment of the conditions indicated by human or automatic controllers; cloud computing facilities for the collection, storage and processing of data over time and ICT systems supporting the information flows.

The domain of information includes mathematical models that describe and predict the thermal behaviour of buildings and of their parts; mathematical models describe the thermal behaviours of heating and conditioning systems, including time performance evolution, data related to ignition times and the achievement of ideal operating conditions, estimation of plant performances in different external conditions.

The domain of control and organization includes management policies, business and service models as well as suitable control systems for residents. Responsible and compliant behaviours are encouraged, while responding to all basic and mandatory requirements in terms of usability and accessibility, capable of satisfying personal demands related to preferences, lifestyles, health and wellbeing issues as well as individual attitudes. The domain also includes control systems that are suitable for the stakeholders and service providers involved in the energy management and service delivery which are able to provide real-time and long-term data, information and KPIs about the local and global performances, to detect problems and critical situations and to support energy management decisions.

In order to manage the design complexity, the control systems were developed with frequent meetings involving industries, research teams and other partners (a cooperative organization offering housing services and service providers in the field) for the purposes of information sharing, constraint and goal alignment, scenario building and validation.

1.3. Benchmark of the Commercial Solutions Available on the Market

TEPORE is a project aimed at supporting the innovation of industrial product and services through the application of knowledge produced in academic research environments. For this reason, the design activities also included a survey of the offer available on the market, also with respect to the control systems. The survey sought to assess the real need to develop dedicated control systems and to respond to certain preliminary questions such as: Which are the basic and advanced functionalities offered by commercial control systems? Do they provide a final solution with respect to the requirements of usability, accessibility and the satisfaction of user needs? Do they provide standardized approaches in terms of functional and interaction features? Do they fit the requirement of flexibility with respect to different typologies of plants (from a technical and management point of view)? Do the existing solutions proposed for smart homes support and promote the sustainable behaviours of inhabitants?

The survey considered some of the most popular control devices, including Nest Learning Thermostat, Ecobee 4, Tado, Netatmo, Honeywell Lyric, Bticino Smarther X8000W, Vaillant vSMART and Beretta BeSMART. The solutions that were analysed demonstrated different control approaches: some propose a dedicated physical device to be installed permanently in the house, offering intuitive access to basic functions and requiring simple gestures for interactions; most solutions offer an application for smart phones, including multiple functions and allowing remote control. All provide information about the status of the system and of the environment (temperature), some, such as Ecobee and Tado, support interaction through voice and some are compatible with the most popular general-purpose personal assistants (Apple Home Kit, Amazon Alexa, Google Assistant).

The physical design of commercial solutions is accurate and refined, indicating the importance of the physical appearance of the control devices, especially those that require permanent installation. A number of dedicated devices (Honeywell Lyric and Nest, among others), are provided with sensors to collect data from the environment and they use artificial intelligence to learn heating conditions and usage habits in the first few weeks to consequently adapt the conditioning performances. Tado also includes sensors to detect the opening of windows, then reacting and switching off the heating. Beretta BeSMART, Bticino Smarther X8000W and Netatmo offer additional devices to be installed in rooms to allow centralized control of the conditioning while allowing different and personalized settings. Most applications offer the opportunity to program the heating of the house on a long- or short-term basis and some (Ecobee, Tado) consider weather forecasts in the control algorithms.

Several applications foster similar visual metaphors to facilitate understanding of the functionalities in the graphical interfaces; for example, the "green leaf" to refer to low energy use. Bticino Smarther X8000W and Honeywell Lyric provide geo-localization of the main users to activate or deactivate heating, depending on the presence/absence of inhabitants. The Honeywell system also notifies out-of-range conditions through smart phone, suggesting suitable interventions.

Our survey demonstrates that the most advanced control systems provide interesting solutions, matching several user needs and offering valuable functionalities for energy saving and comfort optimization.

Nevertheless, for the purposes of the TEPORE, the partners consider the development of dedicated control systems and interface a strategic goal for both energy managers and for the resident. There are multiple reasons for this choice, the main ones of which are listed below:

- from a technical point of view, most solutions pose compatibility issues;
- with respect to the algorithms of energy use governing thermal conditioning, commercial systems are "closed" and do not offer the opportunities for improvements based on monitoring of their effectiveness over time and on adaption to local conditions;
- from the point of view of user needs, while commercial products address most of the requirements that emerged from our investigation, none provides all the functions that the industrial partners of TEPORE were sure to include in the control systems;
- from an industrial point of view, the development of a proprietary control system, referring to the identity of the local service provider, is a strategic issue and a mandatory commitment.

Regarding artificial intelligence that is able to learn from data collection through sensors and to predict situations, the TEPORE partners consider the issue of their reliability and of their efficiency with respect to the current state of the art of technologies and algorithms. In TEPORE, the development of algorithms for the set-up of plants will foster machine learning on historical data and the cross examination of plant performances in the energy manager control system. Instead, with respect to the creation of the control system for residents, artificial intelligence was not considered a solution for anticipating user needs and behaviours for fully automatic controls. The development of a desirable agency of the system for thermo-regulation is still a controversial and open research question and did not fall within the goals of TEPORE.

In TEPORE, the development of the control system for residents should encourage sustainable behaviours, providing automatic and manual functionalities, in order to respond to different user attitudes. The reduction of energy use is encouraged by providing a usable interface, with accessible functionalities and information producing awareness. Moreover, we consider the importance of providing to users a mental model [24] of the functioning of the system, thereby supporting realistic expectations about the thermal performances. In fact, several different factors contribute to making effective prediction of the desirable set-up very difficult: the weather forecasts and behaviours of residents are only partially predictable; the thermal need and requirements relating to comfort are also variable and individual. Furthermore, the conditioning systems and the structures of buildings have a thermal drift that produces delays, sometimes substantial, in reaching the desired temperatures. In addition, many plants have better energy efficiency if they do not work in conditions of maximum energy expenditure, that is when they do not need to operate having to change the temperature in very short space of time. In the opinion of the TEPORE experts, better energy performances can be obtained with an approach that also integrates in the automation algorithms a model of the plant performances that is adapted to the local facilities.

2. A Discussion of the Possible Approaches to the Development of Control Systems

In TEPORE we developed two different controls: those dedicated to inhabitants and those aimed at supporting energy and thermal system managers in the conduction of the heating and conditioning facilities. In some contexts, the set-up and management of the plants is performed directly by the final users of the thermal facilities, that is the inhabitants, as in the case of independent houses with autonomous systems for thermo-regulation. For these contexts, the user and the manager of the facilities for conditioning is one and the same subject. Other contexts, such as condominiums with shared facilities, instead require a control system to be employed by plant maintenance technicians, energy managers and service providers. TEPORE focuses on the second situation and the solutions for sustainability were designed assuming that the most efficient operation of plants must find a compromise between individual requirements concerning the wellbeing expressed by the inhabitants of the units (that can diverge considerably) and the constraints posed by the most efficient functioning of technical facilities. In other words, in TEPORE we assume that minimization of the total consumed energy requires minimization of the demand in each single domestic unit, as is obvious but it also depends on the convenient management of the differentials of energy demand, in time and in space, in a way that is not linear. For this reason, in TEPORE we developed two distinct control interfaces: one for the residents and one for the managers of the conditioning systems (energy managers).

While we recognize that the implementation of a fully automated system would produce a significant reduction in management costs, we point out the fact that the features of the existing conditioning facilities and the complexity of the thermal systems today still require the monitoring and decision-making of human operators. We consider the present state of the art of our research field as being in a transition towards the implementation of a new generation of smart-home solutions that fully exploit the automation potentials of IoTs and data processing. In the transition, while we are testing and refining algorithms and models and working for the diffusion of technical solutions, such as connected sensors, we consider as a priority the development of interfaces and a control platform that support the effective access to information.

The task of investigating and identifying the needs and attitudes of final users (residents) and of the service providers and stakeholders that manage the systems for thermal regulation is therefore a key activity in the development of smart-home solutions, aimed at providing the information which can be used to design the information architecture to respond to needs and to fit in with the decision processes that continue to require manual interventions.

In TEPORE, in order to produce such knowledge, the development of the control systems was conducted within a UX Design approach [25–27]. UX Design aims to guide the development of services and digital applications with a view to maximizing the production of value for final users, service stakeholders and partners. The suitability of the UX Design approach in the development of innovation for sustainability is not new and is documented [28,29]. UX Design provides strategies and design methodologies for the investigations and envisioning of the results of the knowledge produced in the research through maps and diagrams that facilitate the co-design in complex and multiple-stakeholder design environments. Furthermore, UX Design provides the conceptual tools that support developers of digital applications in addressing the variety of human attitudes and dispositions and in organising the information architecture of interfaces.

3. User Experience Design for Resident Control System Development

We report here the activities performed within the TEPORE project with respect to the development of the control-interface for residents. The experimental approach of the project envisages the involvement of inhabitants of the pilot sites at different stages of the product development, from ideation to testing. The users we involved live in condominiums taken as a reference for the entire project, managed by a housing cooperative named Degradi. The Degradi cooperative manages several buildings in Milan and provides a variety of references with respect to the thermal facilities in use. Several buildings have centralized plants for thermal regulation and digital interfaces for control in the home. Typically, the inhabitants are middle-class individuals and families, for whom comfort and cost savings are important. Due to the average cultural level of inhabitants, their economical possibilities and the distributed social characteristics, the residents of the Degradi cooperative provided a suitable environment for the investigation of user needs and attitudes. The managers of the cooperative maintain a close relationship with the residents and their policies aim for a balance between comfort and energy cost reduction. The meetings with the managers of the cooperative produced information about the issues and attitudes of residents, revealing constraints and requirements beyond the trade-off between comfort and sustainability. As an example, the managers reported the criticalities related to the limiting of behaviours, such as the effects of low temperature regulation: due to the effects of humidity, very low indoor temperature during the winter can cause the deterioration of structures while increasing maintenance costs.

The involvement of residents is organized into the following steps:

- user profiling based on questionnaires, interviews and observations in the field (ethnographic survey) resulting in definition of the functional specifications of the control systems;
- realization of interface prototypes, expert analysis and refinement;
- evaluation with representatives of the two user categories and their optimization to achieve solutions whose usability and effectiveness are guaranteed.

The research lead to the understanding of the limits of the existing control systems and to the collection of attitudes and needs of residents with respect to thermal control. We report here the process as well as a number of results that we consider of general interest.

3.1. Method

User preferences and behaviours regarding indoor comfort and the interaction with the thermoregulation system were investigated in parallel through contextual inquiry [30], on line questionnaires [22] and user tests [31]. The decision to apply different research methods [32] sought to better understanding user-perceived and latent needs as each method reveals specific aspects of empirical reality.

The subjects for contextual inquiry and questionnaire compilation were selected by the Degradi cooperative from among its members. The control system applied by the cooperative is produced by one of the partners of the TEPORE project, who is willing to improve the interface usability and the energy savings. The survey was therefore an opportunity to collect feedback about the existing control systems and to investigate the awareness, attitudes and needs of residents with respect to the thermal control at home.

A contextual inquiry was performed in spring 2018 consulting with 5 users in their homes. The users were chosen by the Degradi cooperative as being representative of the members, considering gender, age, family structure, home composition, living conditions and competences. The subjects were: a retired male technician, a couple with an adult son affected by a degenerative disease and a young dynamic female worker. We asked them to demonstrate the use of the thermoregulation system and to speak freely about comfort perception and regulation. The conversations lasted around one hour.

The questionnaires were handed out between March and May 2018, after a beta test with the previous subjects, to a further 280 members of the Degradi cooperative and we received 76 completed questionnaires back from the residents living in apartments distributed across 18 different buildings heated with traditional radiators (26%) and radiant panels (74%).

The questionnaire (see Supplementary Material) is structured into 5 parts: general information on address and number of residents per apartment, home characteristics and heating system, user habits and energy use, user needs and priorities, satisfaction regarding thermal comfort.

The interaction with the thermoregulation system and the redesign of the graphic user interface were structured on the basis of the knowledge of user needs, ascertained through questionnaires and contextual inquiry and on information about energy management provided by experts and companies involved in the project. The phases of research with users and the development of the interfaces lasted around ten months. During this time, a meeting with all main stakeholders of the project was held every month with the purpose of sharing the results and of validating the design choices. The meetings were supported by visual artefacts produced by designers, including system maps, functional architectures and application workflows. Pieces of evidence collected during the research with users were also shared with the project stakeholders, such as the videos reporting part of interviews and the documented interactions with the interfaces. The sharing of these documents contributed to increasing the awareness on the importance of supporting the development of control interfaces with a thorough understanding of user needs and constraints.

After fine-tuning through a number of expert evaluation cycles and having created a prototype control system, user tests are going to be performed. Further refinements are planned to increase the reliability of the system, together with the tests concerning the algorithm for modelling and managing of the facilities.

Focus group with experts and researchers involved in the project and relevant stakeholders were conducted recursively during the project development.

3.2. Results

The contextual inquiry immediately highlighted diverse preferences and behaviours. The first user had professional knowledge of the thermoregulation system due to his previous work as technician in the thermo-technical sector but in any case he was not aware of the diverse functions. Despite the heating through radiant panels in the floor we noticed the presence of a carpet, a choice made by his wife. The inhabitants of the second home we visited had very specific needs regarding high precision in temperature control, as attested by the analogic thermometer place on top of the control system (Figure 2a) and room differentiation needs regarding heating, obtained by adding mobile heat generators (Figure 2b).

(**a**) (**b**)

Figure 2. (**a**) Analogic thermometer placed on top of the existing control system; (**b**) Added mobile heat generator.

The last subject explicitly mentioned difficulties in temperature regulation, giving us a direct demonstration of the tasks required to plan the heating and presenting the user manual and her notes to remember the function she had decided to use (Figure 3).

Despite the relatively low number of subjects, the conversations were very interesting, providing useful insights for the interaction system redesign. The findings were confirmed in focus groups conduced with Degradi experts, Politecnico researchers and partner experts involved in the project.

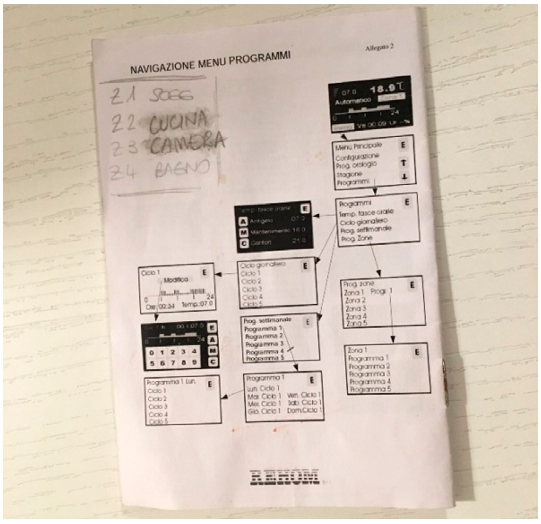
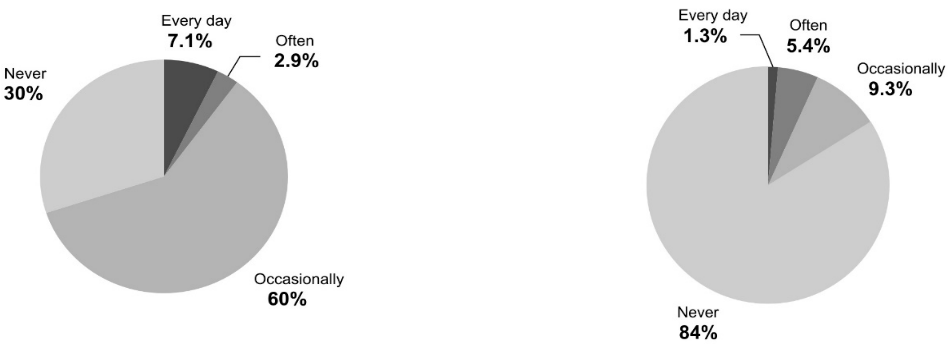


Figure 3. User manual with personal notes.

The visit to the apartments showed that often the furnishing of the houses is realized without particular attention to the thermal aspects. As an example, pieces of furniture such as carpets can be placed on thermal elements, thereby reducing their effectiveness or sensors for thermal control can be placed behind doors and as a result impacting on the precision of the collected data. The interviews reveal quite important correlations between attitudes and social conditions: the attention and interest towards thermal comfort, cost reduction and sustainability seem to depend more on personal needs and attitudes than on age and economic conditions. Some users showed interest in an understanding of the plant characteristics and in the management strategies; others declared their preference for a more interactive control, given better usability of the interface. Users also expressed their interest for temporary changes of the settings, with the “here and now” set-up, possibly with the automatic restoration of default programs (as an example, in the evening hours). Most of them declared an interest in rapid and simple commands to switch between different settings (for example, fast switch off command to be enacted when leaving home for several hours).

The analysis of the questionnaires answers confirmed low interaction of the users with the thermoregulation system: 30% never modify the standard setting and 60% only do so seldom (Figure 4a), 84% never switch the heating off in winter Figure 4b). The users who modify the temperature do it for diverse reasons, the most frequent being in relation to outdoor conditions.

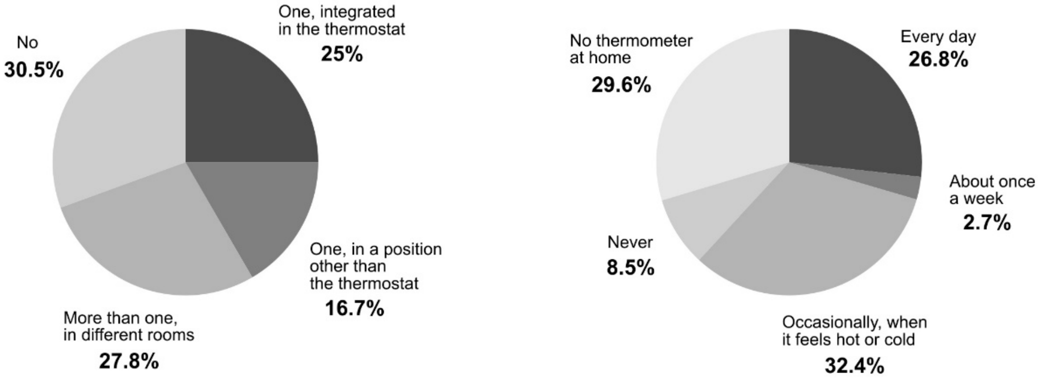


(a) **(b)**

Figure 4. (**a**) Is the centralized setting of the heating elements ever modified? (**b**) Is the heating system ever turned off in winter?

Considering that complete and good satisfaction regarding thermal comfort was stated by 67% of the inhabitants and that the lowest specific satisfaction rate regards consumption and costs, we believe that users are inhibited in regulation by the complexity of the interaction.

In fact, inhabitants seem worried about temperature as pointed out in the contextual inquiry and shown by the presence of several thermometers in the apartments (Figure 5a) and their frequent use (Figure 5b)

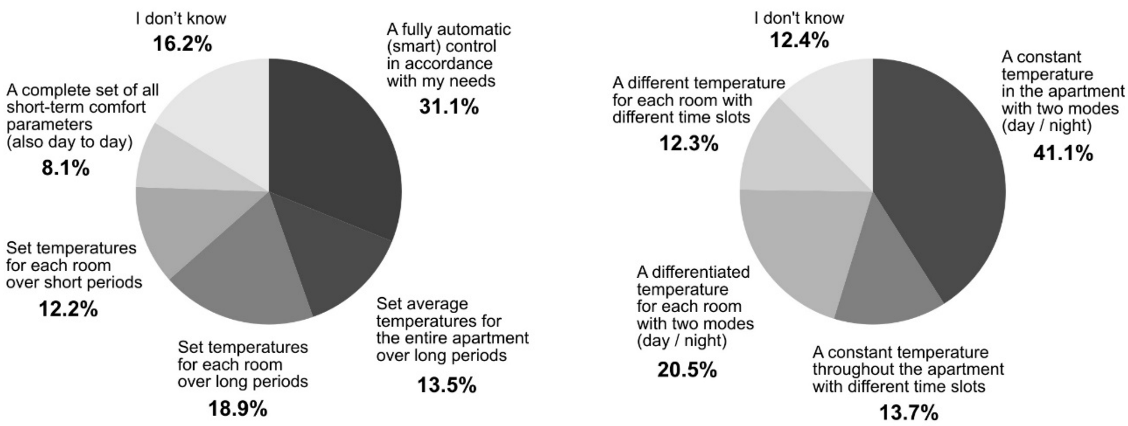


(a) **(b)**

Figure 5. (**a**) Presence of thermometers to monitor the ambient temperature; (**b**) If present, frequency of consultation.

Despite the focus on indoor comfort, residents are not aware of the influence of humidity on thermal perception. In fact, 90% of them do not measure humidity, only 33% have instruments to modify humidity and most of those only use them occasionally.

User preferences regarding automation versus personalization and temperature control reveal a differentiated set of requirements: 31% of the inhabitants opt for a fully automated temperature regulation (Figure 6a). Some prefer a homogeneous temperature in the entire apartment while others opt for independent room regulation. Some prefer long time period choices, others time segmentation during the year and/or the day (Figure 6b).



(a) **(b)**

Figure 6. (**a**) User preferences regarding automatic temperature control and personalized planning; (**b**) User preferences regarding constant temperature or personalized comfort.

The requests differentiation regarding specific information items had already emerged in the contextual inquiry are confirmed. Most inhabitants want to know the temperature in each room;

many are interested in real-time consumption, consumption estimation and tips for consumption reduction (Figure 7).

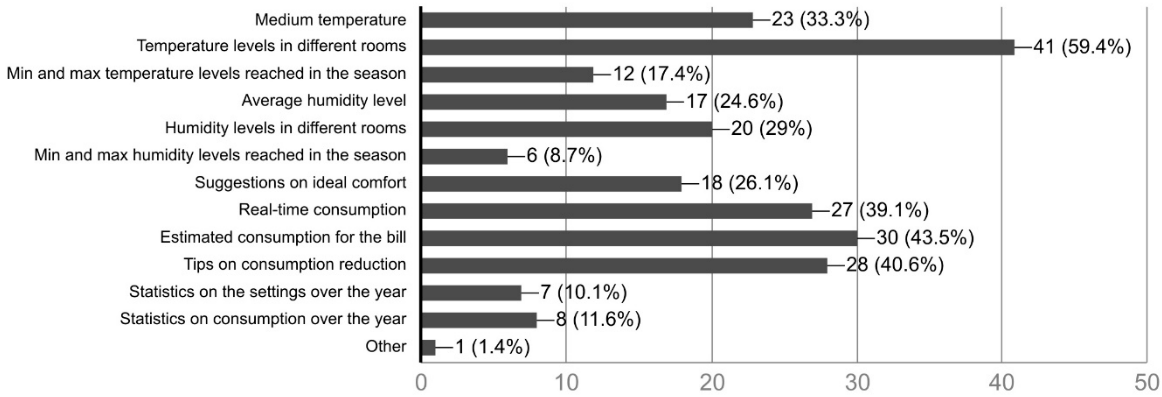


Figure 7. Information required from the control system.

Regarding remote interaction through smartphone, residents seem more interested in receiving information than in controlling the system.

The results of interviews and questionnaires were integrated with the outcomes of the focus groups, also providing reference use cases. The information about user requirements was discussed with the project stake-holders and they were confronted with requirements of the industry that delivers the solutions developed in TEPORE to the market. The presence of smart-home systems contributes to defining the real estate value of an apartment, due to the substantial functional value provided by automation and to the impact on the perceived quality and state of maintenance. For these reasons, the aesthetic characteristics of the control system must be qualified in order to be integrated in interiors of different styles.

With respect to functions, the control was aimed at several different goals: to optimize customized comfort for residents, matching different attitudes and needs; to support and promote efficiency-related behaviours with respect to sustainability by offering functions for the minimization of energy use; to provide functions for the personalization of comfort and energy use that are compatible with the efficient management of plants and with the thermal performances of facilities and buildings (including thermal delay effects); to introduce functionalities for short- and long-term programming; to allow differentiated thermal performances in the various areas of the home; to offer updated information about indoor and outdoor thermal conditions, consumptions, global and local performances of thermal components; to provide guidelines for convenient behaviours; to make remote control possible in full compatibility with the one in the home.

In order to fulfil the needs of different typologies of users and to match the above-listed goals, we defined three different profiles of users that we used as a reference in the development of the functional interface architecture. (Table 1). The intent was to create an interface that is able to satisfy users of all the three different profiles.

Profile 1 includes users that tend to show little interest in interacting with the system. The scarce willingness to interact may be motivated by a limited presence at home and with no binding requirements with respect to thermal conditions or, instead, on steady requirements relating to performances (i.e., the need for constant temperature). It may also be attributed to the disinterest in or inability to be involved in programming. Ageing persons with low technological skills, younger residents spending much time out of the home and with little interest in domestic matters, residents with little interest in comfort and cost savings and others, all belong to the group of users that could be satisfied by a fully automatic system, provided that the expected set-up is maintained with little or no intervention. The main information that the system should offer is that concerning the indoor temperature and the state of the system. With respect to sustainability goals, the main contributions should be provided by the effectiveness of the modelling and of the control algorithms governing the automatic management of the system.

Table 1. User profiles and system requirements.

	Profile 1	**Profile 2**	**Profile 3**
Needs	Standard	Cost reduction Simple personalization	Specific Frequent and detailed inquiring about settings and performances
Availability to cognitive effort	None or low	Low	High
Understanding of the system model	No interest Prefer automated control	Simplified model	High interest
Control requirements	Basic functions and information	Predefined alternatives	Personalized control of settings
Availability to develop technological skills	None or low	Low	Medium
Interest in remote control	No	Yes	Yes
Personalized programming	No	No	Possible

Profile 2 includes persons that are available to interact with the systems, provided that the cognitive efforts are low. Residents willing to use the facilities at the best, while having little skills in the use of digital interfaces belong to this group of users, together with those that have good familiarity with digital interfaces but have little time/interest in the management of the system or who have variable needs and behaviours, making it difficult to plan or predict their presence at home. For these users, we consider the availability of simple pre-defined programs for the settings of the thermal conditions as very convenient, depending on the "here & now" requirements and needing only very few commands.

With respect to the requirements of users of Profile 3, users interested in understanding the control system and taking maximum advantage of it, we consider the importance of providing functionalities for long- and short-term programming based on a personal calendar, including possibilities for the differentiation of the settings for the individual rooms. For this group of users, we consider the importance of providing the full report on energy use and thermal conditions, including external and internal temperatures, in order to allow monitoring and the adoption of personal strategies for comfort and sustainability.

This result is coherent with the literature. As Alan Cooper already stated in the Jetway Test analogy, humans fall into two categories: "Those who turn left strongly desire to be in control and to understand how the technology works and those who turn right strongly desire to simplify their thinking and to have confidence in the success of the flight" [33]. In our proposal we identified a third intermediate category concerning users willing to carry out a simple control without needing to understand how the system works.

According to these profiles, we organized the navigation system in different levels of interaction (Figure 8) and developed a representation of the workflow (Figure 9) applied to share the model definition with the other project partners. The workflow reported here refers to the main control panel, to be permanently installed in a central location of the house. As it is a digital panel that is always visible, when not in use, it is in a low-power (dark) mode, only reporting the indoor temperature of the room in order to reduce the consumption of energy and to avoid introducing undesirable lighting. The interface is turned on with an initial tap.

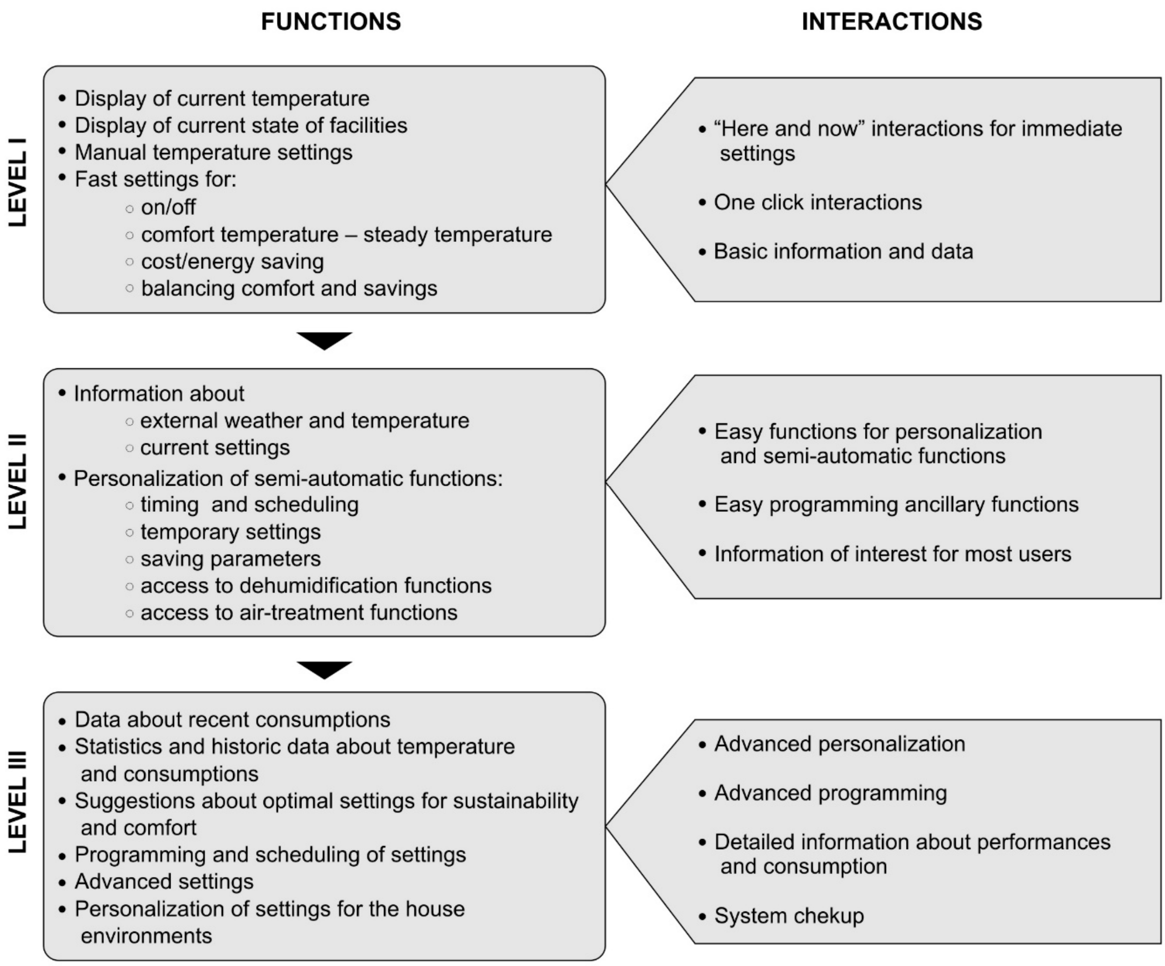


Figure 8. Control system levels of interaction

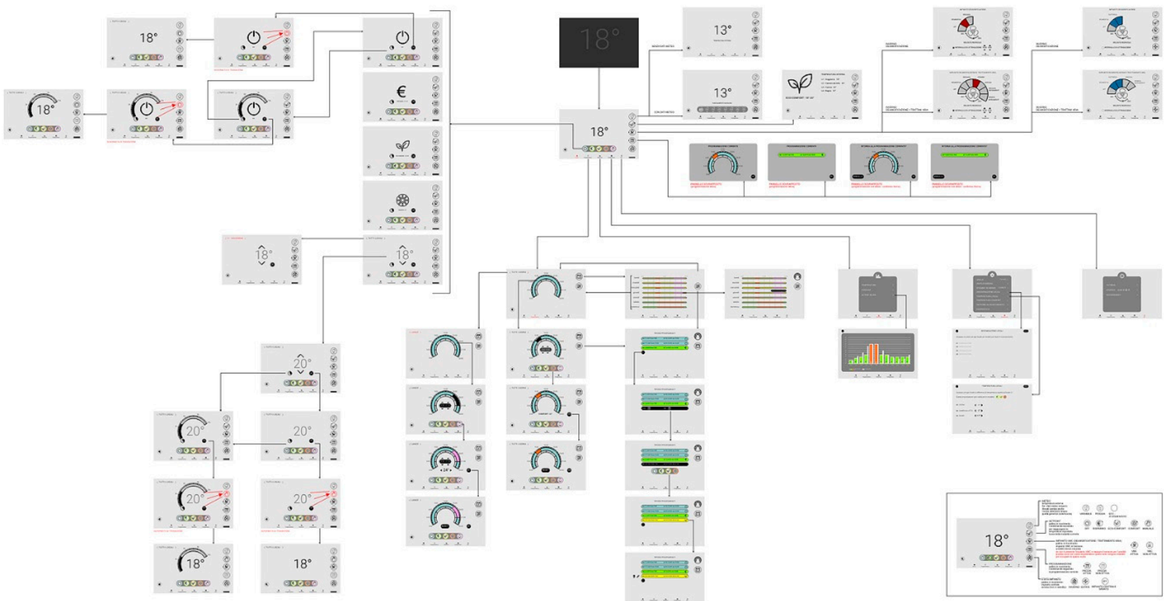


Figure 9. Workflow of the final user interface for system control.

The home page (Figure 10) reports again the indoor temperature and the switch for voice-based interactions (icon in the lower left). Furthermore, the home page includes three different menus—one for the five main direct controls (coloured menu bar just under the temperature display), one for fast and detailed information about the system (vertical bar on the right) and one for advanced programming, settings and reports.

Figure 10. The home page of the interface.

The bar for the direct control includes 5 main functions: one for the switch for immediate turning on/off of the system; one for the setting of an automatic program to provide more sustainable comfort; one preferring comfort over saving; one for setting a tendentially stable temperature state regardless of the external conditions and time of the day; one for the manual setting of the temperature with very intuitive commands (+ and -). The manual control also gives access to timed changes of settings.

The menu on the left provides summary (at a glance) information on the external temperature and weather, on the current settings and program governing the system and on the manual or programmed control status and typology of the plant in operation (heating or conditioning).

The interface was therefore developed starting from the assumption that the system should allow highly intuitive interactions with simple commands (1 to 3 taps) to access automatic programs. Simple and fast access to the different commands is intended to favour a more interactive use of the control system by Profile 1 and 2 users. The functions for programming, monitoring and advanced personalization require more in-depth interaction with the system but are in any case visible on the home page, to encourage users of Profile 2 to exploit the functions for Profile 3.

The new graphic user interface was developed combining textual and visual information, refined in collaboration with expert evaluators and its evaluation takes place through user tests.

4. Discussion and Conclusions

We can summarize the findings of this experimental part of our research by listing a number of results that we consider of general interest. Residents show a variety of needs and attitudes with respect to conditioning and thermal comfort at home, as expected, as well as variable motivation and interest towards knowledge, understanding and control. A commercial control system should therefore meet the requirements of all profiles and we placed the above-reported clustering into three different groups (Table 1) as an acceptable reference for the state of the art of technology. We organized the workflow and information architecture of the application to allow very quick interactions for Profile 1 (level I of the workflow) and important opportunities for the personalization and programming for Profile 3 (level III). We consider the residents of Profile 2 to be very interesting from the point of view of energy savings based on the convenient setting of indoor thermal conditions. We assume that several residents with Profile 2 are receptive to adopting sustainable behaviours if provided with the relevant knowledge and functions, as long as the cognitive effort is low and the benefit is clear. The interface we developed was oriented to this goal.

With respect to measuring the effectiveness of our solution, we consider that the usability tests (still in progress and planned for all the profiles) are mandatory but not sufficient to assess the results.

The interface was developed to optimize usability and to fulfil the requirements of the three user profiles. Instead, the functions offered by the control interface fully reflect the underlying technological system including sensors, the centralized collection and processing of data, thermal models and prediction algorithms. The effectiveness of our integrated approach can therefore be validated on a long-term scale. Also, with respect to full acceptance by users, the validation of the interface requires investigation on a long-term basis in order to be able to verify the impact of information reports and of programming functionalities with a view to enabling more sustainable behaviours.

In TEPORE, the development of the two control systems and the redesign of the residents' interface were carried out in parallel, together with implementation of the thermal model of buildings and facilities and using algorithms for the sustainable operation of plants. Presently, the control systems are in the phases of industrialization and are being implemented in pilot contexts for testing and refinements of interfaces and algorithms. The TEPORE project has provided an opportunity to create innovation through partnership between industries and academia and to explore the potentials of an integrated approach to the innovation of an industrial sector oriented toward sustainability, economic development and the improvement of social wellbeing. The development of the two control systems demonstrated that a UX Design approach based on the investigation of needs, attitudes, priorities and values of all the stakeholders – final users, industries and experts – and on the production of maps, diagrams, workflow, mock-ups and other visual documents, facilitating the understanding of concepts, scenarios and proposed solutions and enabling discussion and cooperation.

TEPORE was an important opportunity for the mutual exchange of knowledge between all the stakeholders and we consider TEPORE a successful project for the following main reasons:

- it provided to all the partners the possibility for a more comprehensive understanding of the complexities and potentials of smart home sustainability solutions;
- it created a network that is able to sustain the innovation of products and processes in industries and to orient academic research, including thermal modelling and algorithm development, toward practical goals and real-world assessment;
- it demonstrated the role of human factors in innovation for sustainability and the effectiveness of research combined with the envisioning tools provided by designers based on their experience, in design contexts with multiple stakeholders;
- it produced knowledge about users' attitudes and needs that could be exploited in other projects.

TEPORE was made possible thanks to the funding support of the Lombardy Region and it was a valuable opportunity for interdisciplinary collaboration and information exchange. As designers, we were asked to become acquainted with the technical complexity connected to the conditioning systems and had the chance to verify the potentials of UX Design in the management of complex design processes, involving several partners and aimed at delivering, in a strict time-frame, products and solutions for industrial purposes. Designers were involved in TEPORE because industries recognize the importance of their contribution with respect to the creation of solutions that are desirable from the point of view of users and the market. In the project, the partners also recognize the contribution of envisioning and synthesis provided by UX Designers to manage the complexity of collaboration between stakeholders.

Moreover, we consider it important to also name certain criticalities that we encountered in the process. As the project evolved, the industrial partner of TEPORE became aware progressively of the impacts of the new solutions on their business model and on the requirements in terms of ICT facilities. As an example, the high quantity of data that an integrated system must collect, storage and process pose several issues, including the cost of facilities, privacy and responsibilities. The creation of systems and services based on cloud data processing and IoTs may require a re-thinking of the business model and of the partners involved in the service delivery or of their industrial capabilities. Our focus as designers was to under the variety of attitudes and needs of users; we also recognize the delicacy of managing personal data [34] that are produced in home automation systems. Furthermore, we recognize as being a strategic issue the creation of incentives to increase the commitment of service providers in the reduction of energy use. ICT and IoT offer valuable opportunities to produce innovation for sustainability but innovation requires investments and identified advantages also from the point of view of revenue. The attention paid by the industrial partners of TEPORE to the economic benefit posed several constraints and we, as designers, consider the importance of developing a better capability to include this factor in the design process.

The digitalization of the control systems for the smart home solution allows considerable advancements with respect to a more sustainable use of energy in domestic environments and provides data for monitoring and strategic management to users and service providers. Meanwhile, the fast evolution of digital operating systems and devices produces risks of rapid obsolescence and of fragility of systems depending on the relevant ICTs. Further development of TEPORE should address the different obsolescence, updating and maintenance requirements of the physical and digital parts of the system with the aim of predicting and manage the optimizing of updating and replacements of parts.

Finally, TEPORE demonstrates that smart home solutions are complex systems that should be classed and designed as socio-technical ones. The evolution of socio-technical systems is accompanied by a change in the roles of the actors, including technical, professional, economy-related and political stakeholders [35–38]. Disruptive changes, even when they appear beneficial from the sustainability point of view, can encounter obstacles as they are being fulfilled due to the need for the evolution of social actors and of industrial ecosystems. The development of services and systems for sustainability should take into account the complex tangle of needs, habits, priorities and cultural factors that influence final users and should also promote the evolution of business models and of organizations in order to be able to enjoy the positive contributions combined with adoption of the required changes by all actors.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/13/3632/s1, TEPORE project questionnaire.

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