Health, well-being and comfort in smart buildings innovation: state-of-play and opportunities.

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Abstract. The market of smart building solutions aiming at improving the comfort, well-being and health of occupants, but also the inclusiveness and accessibility of the building to people with more specific needs is growing. More and more smart solutions, as well as standards, certifications and public regulations are currently being developed, but a more global and systemic approach seems to be missing. The paper reviews the status of research related to the means and methods enabling interactions with occupants in smart buildings, which feeds an iterative approach with European industry and research actors aiming at collectively identify barriers and opportunities in this area.

1. Introduction

The market of smart building solutions aiming at improving the comfort, well-being and health of occupants, but also the inclusiveness and accessibility of the building to people with more specific needs is growing. More and more smart solutions, as well as standards, certifications and public regulations are currently being developed, but a more global and systemic approach seems to be missing. This paper investigates the role of smart technologies in relation with comfort, well-being and health, with a view of gathering knowledge from professionals and researchers communities thanks to an iterative approach.

While well-being, comfort and health are concepts more and more looked at in the building industry, it is of course broader and already significantly addressed in other domains. Still, there is no consensus amongst the scientific communities addressing the built environment. The following section 2 provides some definitions and elements of context to delimitate the focus of the paper, and section 3 develops the specific research questions and adopted methodology. A broad community of researchers addressing smart buildings tackle these questions from various disciplines: civil engineering, architecture, informatics, and even psychology and social sciences. A literature review is reported in section 4. Section 5 eventually delivers the outcomes of Focus Groups discussions with stakeholder enabling to frame the barriers and identify the opportunities for smart building innovation communities.

2. Definitions and context

Hanc et al. [1] “established the most prevalent and insightful definitions and dimensions of wellbeing in buildings applied in the recent published literature” as depicted in Figure 1. Quite heterogeneous aspects are reported, covering perceived and sometimes subjective criteria linked to psychological and social Factors.

Based on detailed literature review of definitions related to indoor environment quality (IEQ), Rohde et al. [2] proposed a three-branched framework to define the "good indoor environment", equally relying on comfort, health and well-being. In their paper, the authors propose the following definitions [2]:

- *Comfort: indoor environment conditions that facilitate a state of satisfaction of bodily wants in occupants, based on their individual preferences and their given activity, and that limit physical stressors causing annoyance.*
- *Health: indoor environment conditions that promote physical resilience and restitution of occupants, and limit physical stressors causing infirmity, disease and years of potential life lost.*
- *Well-being: indoor environment conditions that afford mental resilience and restoration, offer variation, provide controllability and advance positive stimuli to improve occupant happiness.*

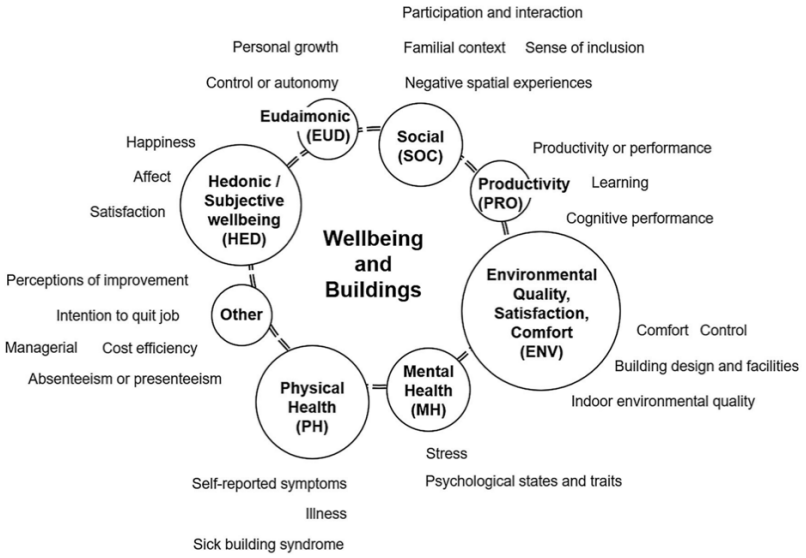

Figure 1: Themes associated to well-being in buildings, extracted from [1]**.**

With the buildings occupants requesting more consideration for the quality of their indoor environments (where they spend more than 80% to 90% of the time), and the construction and real-estate industries pushing for more recognition of the investments in Indoor Air Quality technologies, public and private initiatives emerged to define and value IEQ.

Level(s) is the European Commission framework aiming at providing a common language for assessing and reporting on the sustainability performance of buildings. Level(s) offers an extensively tested system for measuring and supporting improvements, from design to end of life. It can be applied to residential buildings or offices. It is made up of 6 macro-objectives and 16 performance indicators. Macro-objective 4 is called *Healthy and comfortable spaces*, and includes performance indicators on Indoor Air Quality, time outside of thermal range, Lighting and visual comfort, and acoustics and protection against noise, as shown in Table 1.

Table 1. Indicators related to health & comfort in the EC Level(s).

4. Healthy and comfortable	4.1 Indoor Air Quality	Parameters for ventilation, CO2 and humidity Target list of pollutants: TVOC, formaldehyde, CMR VOC, LCI ratio, mould, benzene, particulates, radon

spaces	4.2 Time outside of thermal comfort range	% of time out of range during the heating and cooling seasons
	4.3 Lighting and visual comfort	Level 1 checklist
	4.4 Acoustics and protection against noise	Level 1 checklist

Based on engineering-related physical values and models, Level(s) therefore focuses on health and comfort.

Moreover, several commercial building certification schemes address well-being and comfort:

- BREEAM (Building Research Establishment Environmental Assessment Method), the world's first sustainability rating scheme for the built environment. BREEAM focuses on measuring and reducing the impacts of buildings and in doing so, create assets that are better for people and the environment.
- The Leadership in Energy and Environmental Design (LEED) rating system provides a framework for healthy, highly efficient and cost saving green buildings. It is for all building types and all building phases including new construction, interior fit outs, operations and maintenance and core and shell.
- The WELL Building Standard™ (WELL) was the first building standard to focus exclusively on the health and wellness of the people in buildings. It is a performance-based system for measuring and certifying features of buildings that impact human health and well-being, through air, water, nourishment, light, fitness, movement, thermal comfort, sound, materials, mind and community. It marries best practices in design and construction with evidence-based medical and scientific research – harnessing buildings and communities as a vehicle to support human well-being.
- The FITWELL standard provides tailored scorecards for existing and new buildings and sites. It counts seven health impact categories: impact on Surrounding Community Health; reduction of morbidity and Absenteeism; Support to Social Equity for Vulnerable Populations; Feelings of Well-Being; Access to Healthy Foods; Occupant Safety; Increases Physical Activity.
- The Living Building Challenge defines measures of sustainability for new and existing building, interior, landscape or infrastructure. The certification addresses 20 imperatives which are grouped into 7 "petals": Place, Water, Energy, Health + Happiness, Materials, Equity, Beauty.

These certification schemes provided as examples show the range of domains requested by building developers and owners, and the related aspects they are looking for in terms of comfort, health and well-being, as expected by their customers.

With the expansion of "smart buildings", the automation of the buildings' technical systems operation is increasing, promising ever better performance and efficiency, while adapting to the needs of occupants. According to Buckman et al. [3] "smart Buildings […] integrate and account for intelligence, enterprise, control, and materials and construction as an entire building system, with adaptability, not reactivity, at the core, in order to meet the drivers for building progression: energy and efficiency, longevity, and comfort and satisfaction. […]".

The energy efficiency associated with the operation of buildings' technical systems has been extensively addressed in academic research and already transferred on the market, with intelligent products in the fields of heating, ventilation, conditioning, facades, or the use of renewable energy sources.

Besides, a building's "smart behaviour" should match and even increase the occupant satisfaction [4]. The balance amongst energy efficiency and occupants comfort, health and well-being can then be seen as a "trade-off" problem, which can be addressed by several means, ranging from intelligent automation (where the actuation relies on prediction) to systems enabling occupants to interact (providing feedback or manually actuating).

3. Research question and methodology

This research paper is part of a H2020 Coordination and Support Action: the SmartBuilt4EU project[1]. Amongst other objectives, it aims to facilitate the exchange of information between EU-funded projects and national initiatives in the field of smart buildings and the related business, policy and media. SmartBuilt4EU consolidates a *Smart Building Innovation Community* with, at its core, EU-funded projects, their partners and collaborating institutions.

The project has set up four task forces investigating issues related to smart buildings: their objective is to identify the remaining challenges and barriers to smart building deployment, and the associated research and innovation gaps that should be addressed in the near future.

This paper refers to the Task Force 1, which investigates how the interactions between any smart building and its users can be facilitated and improved, as a key success factor for the market uptake of smart building solutions. The specific topic addressed by this task force and presented in this paper is *occupant-centric building for enhance quality of life*, which aims to address these questions of comfort, health and well-being.

Based on an iterative approach involving market stakeholders and researchers, the Research Questions are formulated as follow:

- RQ1: Beyond the existing standards, can we agree on the definitions of comfort, health and wellbeing?
- RQ2: What are the specific parameters, methods and means (technical , social etc) enabling user centric building? What specific parameters are attached to enhanced well-being, inclusiveness, and health?
- RQ3: How to deal with potential heterogeneity of users, across generations, countries/regions, gender, socioeconomics, etc.?

Given the broad scope of the topic, and the rapid pace of research and development, as well as the commercialisation of technologies, a flexible research methodology is required. The paper relies on a *literature review* feeding *focus group discussions*, with experts of the smart buildings market and research domains. The proposed research methodology is depicted in Figure 2.

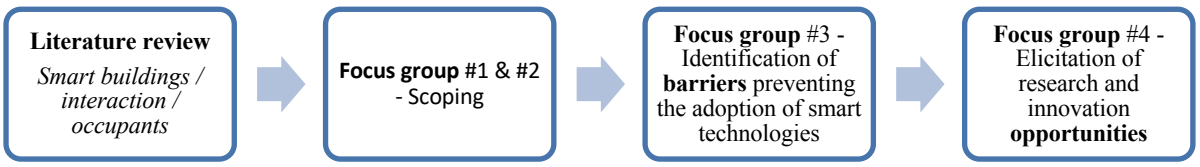

Figure 2: Research methodology adopted.

4. Literature review

A literature review comprising more than 130 publications was conducted to identify the status of knowledge and scientific outcomes relevant to the Research Question. The purpose of this literature review is to highlight the *means and methods related to the interaction with occupants in smart buildings*. It is aimed at providing a background analysis to the members of the Focus Groups in terms of applications, technologies and scientific approaches in relation with the field.

In order to identify scientific papers addressing the means to *interact with occupants in smart buildings*, the Scopus database has been used in Spring 2021. The query was formed as follow:

(TITLE-ABS-KEY (*smart* AND *building*) AND TITLE-ABS-KEY (*occupant*) AND TITLE-ABS-KEY (*interaction*))

It provided a corpus of 134 papers. A manual selection has then been applied, in order to select a final set of papers dealing with smart building and comprising means for interacting with users, providing with a final list of 118 papers.

A rapid analysis shows that out of those 118 papers, 70 refer to "*comfort*" (57%), 28 mention "*health*" (25%) while only 24 contain "*well being*" (20%).

[1] https://cordis.europa.eu/project/id/956936, accessed February 18, 2022

Figure 3 and Figure 4 give a weighted overview of the keywords indexing the papers. Figure 3 depicts the keywords applied by the indexing system, while Figure 4 shows the keywords as defined by the authors. A look at those word clouds shows that *energy efficiency* (also *energy conversation*, *load monitor*ing) and *human comfort* (also *thermal comfort*) are dominants topics in relation with *smart buildings* (also *intelligent buildings*, *smart environments*).

Figure 3. Index keywords.

Figure 4. Authors keywords.

Investigating more into this corpus, we looked at the paper dealing specifically with "*energy"* or "*comfort"* or "*energy and comfort"* in order to identify the most common application areas (Table 2). Interestingly, within this corpus, research addressing both energy and comfort often focus on personalized energy systems (HVAC), lighting and active facades.

Table 2. Applications in relation with energy, comfort and both

Papers dealing with:	Main applications
Energy	HVAC optimization, Appliances & event detection, awareness of resource use
Comfort	Visual discomfort, Thermal comfort, novel IAQ sensor devices
Energy & Comfort	Personalized comfort, ventilation, conditioning, lighting, automated façade, occupant-façade interaction, adaptive actions, blinds and window operation, heat balance approach, holistic approaches

In order to inform the Focus Group discussion, a specific analysis of the means and methods enabling the interaction with the occupants has been carried out on the 118 papers, and is revealed in Table 3. The modelling and detection of occupancy is clearly a recurring scientific topic, indicating that the existing smart technologies might be improved in the near future in this regard. Moreover, a broad range of papers address the means for interacting with occupants, either actively (through apps and other devices, enabling " […] *adaptive actions from the occupants to restore their well-being*" [4]) or passively (by systems adapting to the status or indirect feedback of the occupants).

Table 3. Technical means for interaction with occupants, analytics and data-related methods

Occupancy	Occupancy modelling [5], occupancy detection [6][7][8][9][10][11], event detection [12][13][11]
Interaction	Lighting [14][15], Gamification [16][17], Smart Home simulator [18], Mobile application [19], interactions of occupants with building systems [20][21][22][23][24], including automated facades [25][26][27], interactive systems for energy consumption awareness [28][29], smart mirrors [30]
Data-related & AI method	(Deep) reinforcement learning [31][32][33], disaggregation [34], linear regressions [22], Bayesian modelling for incorporating occupant feedback [35], cyber-risks analysis and blockchain [36]

Table 3 also mentions the data-based methods applied in the papers reviewed, indicating Artificial Intelligence is at the core of numerous research and innovation projects.

5. Focus groups organisation and findings

Based on the outcome of the literature review, the next step in the data collection relied on focus groups, in the form of structured brainstorming sessions.

Forty six professionals related to the built environment contributed to the Focus groups: 53% of them were researchers from technical research centres and academia, covering different engineering and social studies fields. 40% came from private businesses, while the last 7% represented industrial associations from the construction sector. 36% of the participants were female. Contributors came from a variety of European countries including France, Greece, Poland, Italy, Finland, Slovenia, the Netherlands, the UK, Luxemburg, Spain and Switzerland.

Guided by a facilitator, four 2-hour sessions have been organised:

1) a kick-off #1 meeting (hybrid session),
2) an online workshop (#2) focused scoping the concepts considered,
3) a workshop (#3) on barriers and drivers,
4) a final workshop (#4) on the gaps and opportunities.

Each of the sessions gathered at least 50% of the registered experts. The contributions of the participants have been requested in a structured collaborative process, and collected and saved in a remote whiteboard system (conceptboard.com).

The following sub-sections detail the outcome of the sessions #2, #3 and #4.

5.1. Scoping the key concepts

The group of experts has been gathered in session #2 with the aim of better scoping the topic studied, on the basis of the key outputs of the literature review. A rich variety of definitions and points of view has been elaborated by the participants. While some of them relied on the more engineering-oriented approaches to comfort (citing i.e. EN16798 standard), other definitions were suggested such as the role of buildings in protecting against disturbing or harmful events, the inclusion of security or parental constraints in the design, or even the ability of built environment to host food production (gardening). The overall role of buildings in providing resiliency in the context of climate change was largely accepted in the group.

The group also confirmed the findings in relation with technology progress. The increasing offer in (cheap) Indoor Air Quality sensors is accompanied with an increased awareness of occupants regarding Air Quality, especially in post-COVID times. Means and devices to interact with occupants is becoming prominent as well, as the users need to be part of the operational management of their environments. The use of AI methods was also mentioned as very efficient, still with a clear need for users to feel in control of the operations, and potentially to be able to influence it.

5.2. Elicitation of barriers preventing the adoption of smart technologies

Session #3 was intended to discuss the barriers in the adoption of smart technologies targeting user comfort, health and well-being. The discussion has been structured around 5 key barriers: technical, economic, social, value chain and regulation. The outcomes are summarized in Figure 5.

The group identified *technical barriers* in relation with the collection (sensing) and quantification (analysis) of data in relation with comfort, health and well-being. These topics are indeed quite subjective, and we still lack standard and indicators at the EU level. *Economic* issues were also clearly mentioned: when it comes to valuing these novel smart systems, costs and benefits are not clearly reported yet. The *social* acceptance has been largely discussed then, both in terms of subjective perception (which leads to very distinct understandings) but also in terms of general interest for the appropriation of such new technologies. Barriers related to the *value chain*, and its economic actors have been addressed too, and the group recognized the fragmentation of the commercial offer today, with both (very) large and (very) small players on the market, and a demand/offer which is not well balanced. The coming development of standards and *regulations* could change this situation, as it is usually the case in the construction/real estate industry. A specific point of attention discussed is privacy management. While some services start getting more customized in Europe, the EU's General Data Protection Regulation (GDPR) constraint seems to appear as a limit to user profiling. This is relevant when it comes to comparing the share of smart technologies in EU against other regions.

Figure 5. Summary of the barriers

5.3. Opportunities

During the final session #4, the group discussed the opportunities for filling the gaps. Several types of activities are described in the table below, in relation with research & innovation, demonstration, scaling-up and industrialization, certification/standardisation and regulation.

Table 4 summarizes the opportunities discussed.

Table 4. Opportunities identified by the Focus Group.

	Activities
Research & Innovation	• Develop global methods & sensitivity algorithms linking (measurement) data and (comfort / well-being) KPIs. This includes the use of AI and self-learning systems. • Improve human models for thermal comfort simulations. That means an anthropometric big effort in many EU countries to have specific values for temperature and ventilation problems. Wearables can help achieve this goal. • Strengthen the development of open-access databases of monitored buildings (including sensors data and occupants questionnaires). • Propose a harmonised method to calculate the most common comfort indicators, to integrate them with new KPIs related to non-energy benefits. • Develop/upgrade tools and processes to collect data on well-being and identify priorities for occupants.
Demonstration	• Identify living labs (large scale demonstration sites that have a longer lifespan than individual EU projects, starting with tertiary sector) and equip them with trust-worthy measurement tools to improve testing and validation. • Demonstrate applications of adaptive comfort models and occupant-driven strategies and technologies. • Use design thinking methods with users/customers for better defining objectives, data and further integrated functionalities.
Regulation &	• Make the building logbook mandatory, with items related to comfort, both in

legal framework	terms of actual conditions and continuous monitoring of the perceived comfort.
Scaling-up and industrialization	• Facilitate contact and interactions between building owner, facility manager, and building users. • Develop pre-commercial procurement (with public entities). • Map the smart solutions ensuring the monitoring and follow-up to requirements of Sustainable buildings (DGNB, BREEAM...) and well buildings (WELL etc) to generate market expectations.
Certification & standardisation	• Deploy user-centric standard(s) that could be adopted at building's early design phase and based on EU values and perspectives (Level(s), BREEAM, WELL). • Make certification process easy, affordable and accessible for all stakeholders. • Consider evolutions of certification from a static picture (actual conditions) to real time control and procedures (monitoring of perceived comfort).
Upskilling & awareness raising	• Conduct "evangelisation" of occupants, property managers, insurers, about smart technology benefits on well-being in buildings, to create market demand. • Develop training, demos and social business cases towards electricians and installers on the relation between building solution performances and well-being perception.

From a construction informatics perspective, these opportunities remain quite challenging, with regards to data-related methods and AI (as highlighted in Table 3) as well as to the means (interfaces) enabling a building to interact with its human occupants. The sensing of building conditions, and the overall data management [37], including the interpretation of its users perception, also require a global, holistic approach underpinned by semantics.

6. Conclusion

The paper presents the results of an industry-based study aiming at identifying the role of smart building technologies in relation with occupants' comfort, health and well-being. It aims to highlight the status of current research and development, as well as the already commercialized solutions, define the gaps faced today and eventually identify opportunities to broaden the use of those technologies.

The proposed methodology is applied as part of a European Commission-funded project, SmartBuilt4EU, and highly relies on the involvement of stakeholders from the construction and real estate industry and from the research and innovation community. The paper summarizes the findings of a literature review which feed a series of Focus Groups with experts.

The main conclusions, in relation with the Research Questions, are spread throughout the literature review, barriers and opportunities sections. In relation to RQ1, the literature provides knowledge on the definitions of comfort, health and wellbeing, as reported in the introduction section. Still, the discussions engaged with the experts show that there are significant differences in their understanding, probably influenced by the range of disciplines involved, from engineering to social science. Comfort (in particular thermal comfort) and Health (more precisely Indoor Environmental Quality) are the most usual understanding in literature, while well-being is detected in commercial certifications. The literature review informs on the specific parameters, methods and means enabling the interaction with users, related to RQ2. In our corpus, a majority of research papers is focused on comfort, while health and well-being seem to be more a concern for the commercial certifications (e.g. WELL, FITWELL). The experts however identify a clear social barrier associated with the understanding of the underpinning parameters, and the potential influence of smart technologies, requiring more research and demonstration activities. RQ3 has been largely addressed in the Focus Groups addressing the scope and the barriers. Indeed the highly subjective perception of comfort and well-being in particular makes it challenging for smart systems to deal with the heterogeneity of buildings users (including the culture, generations, countries/regions, gender, socioeconomics). The outcomes of this Task Force are expected to be turned into recommendations for future research and innovation programs.

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