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Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings

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Abstract

This study introduces an interdisciplinary framework for investigating building-user interaction in office spaces. The framework is a synthesis of theories from building physics and social psychology including social cognitive theory, the theory of planned behavior, and the drivers-needs-actions-systems ontology for energy-related behaviors. The goal of the research framework is to investigate the effects of various behavioral adaptations and building controls (i.e., adjusting thermostats, operating windows, blinds and shades, and switching on/off artificial lights) to determine impacts on occupant comfort and energy-related operational costs in the office environment. This study attempts to expand state-of-the-art understanding of: (1) the environmental, personal, and behavioral drivers motivating occupants to interact with building control systems across four seasons, (2) how occupants' intention to share controls is influenced by social-psychological variables such as attitudes, subjective norms, and perceived behavioral control in group negotiation dynamic, (3) the perceived ease of usage and knowledge of building technologies, and (4) perceived satisfaction and productivity. To ground the validation of the theoretical framework in diverse office settings and contexts at the international scale, an online survey was designed to collect cross-country responses from office occupants among 14 universities and research centers within the United States, Europe, China, and Australia.

Keywords

Interdisciplinary Framework, Occupant Behavior Survey, Office Buildings, DNAS Framework, Social Cognitive Theory, Theory of Planned Behavior.

1. Introduction

In 2016, the building sector consumed more than one-third of the world's primary energy [1]. Reducing energy use in buildings remains a critical strategy to minimizing greenhouse gas

(GHG) emissions and meeting energy policy and efficiency goals world wide. An international energy evaluation [1] confirmed that offices make up a significant segment of the commercial building sector, which, in turn, represents the fastest growing energy demand sector—with an average consumption increase rate of 1.6% per year from 2012 to 2040. Energy is consumed in office buildings for heating, ventilation, cooling, artificial lighting, and plug-in equipment [2]. However, energy use is strongly influenced by other factors as well, including the availability and efficiency of building control systems, their management, and their operation.

Today, people spend an average of 90% of their time in buildings [3]. Accordingly, energy is consumed in office buildings for maintaining comfortable and healthy environments for the occupants, and by occupants for operating computers and interacting with control systems and other technological equipment. Since the 1990s, companies have realized that building occupants are one of the largest budget items in office buildings [4]. Related costs of course include employment rates, but also include productivity and medical insurance covering working conditions (i.e., those related to health, safety, and comfort of employees) [5]. The average cost of providing health care can be up to 7.6% of a company's annual operating budget in the United States [6]. Increasing occupant's satisfaction with their office environment has become a way of improving productivity and reducing operational budget costs—thus increasing profitability for companies [7].

Occupant behavior research over the last decade primarily focused on the observation, understanding, and prediction of the behavioral phenomena in the office building sector [8, 9]. Using information gained from the disciplines of building energy and social-psychology, research presented in this paper embraces a new interdisciplinary branch of occupant behavior research focusing on the link between occupant behavior, building controls, and energy-related consumption effects [8], driving innovations for building technology adoption in the commercial building sector.

1.1. Needs for interdisciplinary studies

It seems timely to consider occupant behavior in buildings from an interdisciplinary perspective. Researchers now broadly recognize the contextual (rather than purely environmental) factors influencing the human-building interaction [10-17]. Explorations regarding the achievement of energy-efficient usage in the building sector are today established around the understanding of the socio-technical link between building occupants' behavior and the use of building technologies, energy services, and controls [9]. Abrahamse, et al., [12] anticipated this interdisciplinary approach as a two-way exchange of knowledge from socio-technical disciplinary fields of sciences: "*sociologists can provide more insight into macro-level factors that shape […] energy use. Also, input from environmental scientists can be of valuable importance to further improve intervention studies. The environmental sciences can help translate energy-related behaviors […] into their environmental impact, e.g., in terms of CO2 emissions, and help select high-impact behaviors.*"

A significant contribution towards the configuration of an interdisciplinary approach for understanding occupant behavior, comfort, and satisfaction impacting the achievement of high-performing buildings has been provided by researchers in the field of architecture [18] and social science [19]. Day and Gunderson [18] proposed a methodology blending disciplinary perspectives and research techniques stemming from interior design, building science, data science, and social science. The architects endorsed the hypothesis that occupants receiving effective training on how to use building technologies and energy systems were significantly more likely to be comfortable and satisfied with their office environment. By focusing on the highlight of social-psychological factors of energy concerns affecting employees' energy saving intentions within the workplace, Chen and Knight [19] contributed to the confirmation of the role of social scientific perspectives in energy research. These results are significant to the extent that social psychology theories, analytical methods, and insights can provide measurable improvement in promoting energy conservation, which is affected by both behavior and technology.

Advances in interdisciplinary research have emerged through the integration of multiple theories in the definition of frameworks organizing the human-building interaction issue. Supported by the vast amount of available energy consumption and human-related data, together with the advancements in big data analysis techniques, scholars [20] proposed an interdisciplinary research framework at the boundaries of energy and social sciences bounded with data information science. A conceptual framework for assessing energy use in the domestic sector was developed by Kowsari and Zerriffi [21]. Recently, Von Grabe [22, 23] postulated a systematic framework for the energy-related human-building contextual factors aiming to a synergetic organization of this interaction phenomena in buildings. Similarly, Wolske, et al. [24] introduced an integrated framework that combines variables from behavioral theories to explain consumers' interest in residential solar photovoltaic systems. Also based on a theoretical framework integrating multiple theories and disciplines, Li, et al. [25] developed a survey instrument aiming to gather interdisciplinary knowledge on energy use behavior in buildings. Li's study provided survey data for statistical-based models of occupant behaviors, useful to provide insights into occupant energy saving behavior and characteristics as a function of occupant motivation, opportunity, and ability to interact with building technologies. Importantly, Li's study also provides useful suggestion on occupant interventions. Research from Allison [26], Axsen and Kurani [27], Ryghaug and Toftakerare [28], Sheller and Urry [29], and Sovacool [30] confirm that while disciplinary theories contribute important understandings of the behavioral phenomena, blending aspects of interdisciplinary theories can provide additional interpretations and insights. In this picture, further research integrating multiples theories, comprehensively describing the energy-relevant human-building interactions in office buildings based on the knowledge of interdisciplinary fields, will provide beneficial data.

1.2. Scope of work

The goal of this paper is to develop a new interdisciplinary framework, synthesized from building physics and social-psychological theories, to enable socio-technical knowledge exchange and co-learning on the human-building interaction phenomena. Based on this study, a questionnaire and associated measurements will provide data-driven information to ground the validation of the theoretical framework at the international scale. The questionnaire will enable interdisciplinary and cross-country data gathering. One of the objectives is to transform the knowledge discovered through large-scale survey data into behavioral-based energy efficiency solutions and insights, taking into consideration not only the energy metrics and physical properties from building physics, but also the contextual aspects of energy-related behaviors in the workspace. The paper is structured as follows.

- Section 2 introduces three theories and the ontology synthetized to explain energy use behaviors: the social cognitive theory (Section 2.1), The drivers-needs-actions-systems framework (DNAS) (Section 2.2), and the theory of planned behavior (TPB) (Section 2.3). The strengths of the proposed integrated framework compared to each individual existing theory are rationalized (Section 2.4).
- Section 3 illustrates the proposed research framework and the key research questions associated with four learning objectives: motivational drivers (Section 3.1), group behavior (Section 3.2), ease and knowledge of control (Section 3.3), and satisfaction and productivity (Section 3.4).
- Section 4 explains the survey design procedure, including selected description of measures (Section 4.1) and strategies for sampling and participant selection (Section 4.2), mitigation effects on the self-reported bias (Section 4.3), and translation guidelines (Section 4.4).
- Section 5 discusses benefits of (Section 5.1), advancements in (Section 5.3), and barriers to (Section 5.4) the proposed interdisciplinary research synthesizing building physics and social psychology.
- Section 6 provides a conclusive summary and highlights further research plans.

2. Integrated theoretical frameworks

Building on the emergent trend in energy and social sciences research, the goal of this study is to develop a data-driven research framework integrating multiple theories and interdisciplinary aspects. Together with a pool of researchers in the context of the International Energy Agency Annex 66 "Definition and Simulation of Occupant Behavior in Buildings" activities [31], the study explored and combined theories and insights from the technical and social dimensions of human-building interactions to support research in the fields of building and social sciences to better quantify the influence of occupant behaviors on building energy performance [8]. The proposed research framework is based on social cognitive theory (Section 2.1), the DNAS framework for energy-related behaviors (Section 2.2), and the theory of planned behavior (Section 2.3).

2.1. The social cognitive theory

The social cognitive theory (SCT), explained by Bandura [32], describes human behaviors as a dynamic interplay of environmental, personal, and behavioral factors (Figure 1). According to SCT, people learn a certain behavior by observing others with the influences of these three factors (triadic reciprocal determinism). In other words, what people perceive (environmental physical and social factors, comfort, and control), believe (personal factors), and do (exercised past behavior), affect, in turn, the way their and other people's behavior (exercised future behavior) [32]. By applying SCT, this study attempts to foster investigations on how occupant perceptions of their physical and social environment (such as building characteristics), social norms in the workspace dynamic, as well the perceived comfort sensation and behavioral control over the shared indoor environment affect reported behavior. In turn, this knowledge became a functional predictor for their intention to behave in the future.

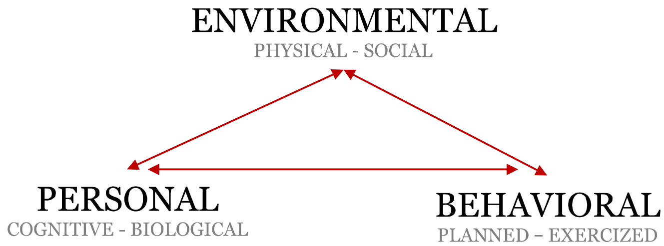


Figure 1. *The triadic reciprocal determinism of environmental, personal and behavioral factors of the SCT*

2.2. The drivers-needs-actions-systems framework

Previous research [33,34] showed that cognitive theories of human behavior borrowed from psychology and social science corroborate significant insights for the conceptualization of an interdisciplinary framework of energy-relevant human-building interactions. Several frameworks have been theorized over the last 40 years, charting human behavior using a need-action-event cognitive process. In the effort to define a standardized ontology describing energy-related occupant behavior phenomena in buildings, the DNAS framework was developed, representing the four key elements of drivers, needs, actions, and systems [33] (Figure 2). The DNAS framework is based on nine cognitive-behavioral theories that capture the stochastic nature of the human cognition process by describing the connection between the human "inside world" inputs (drivers and needs of behavior) and the environmental "outside world" outputs (actions and events within the building). The DNAS defines that occupant behaviors come under the consequence of stimuli (drivers of behavior) from the social and physical environment (i.e., social norms, environmental factors) to accomplish personal cognitive and biological needs (i.e., privacy, physical comfort). These correlations are used to explain and predict occupant's actions on the control systems. The DNAS framework provides a cause/effect ontology describing the occupant-building interaction phenomena, enabling data translation into both machine- and human-readable computational models of energy-related occupant behavior for building performance simulation [34].

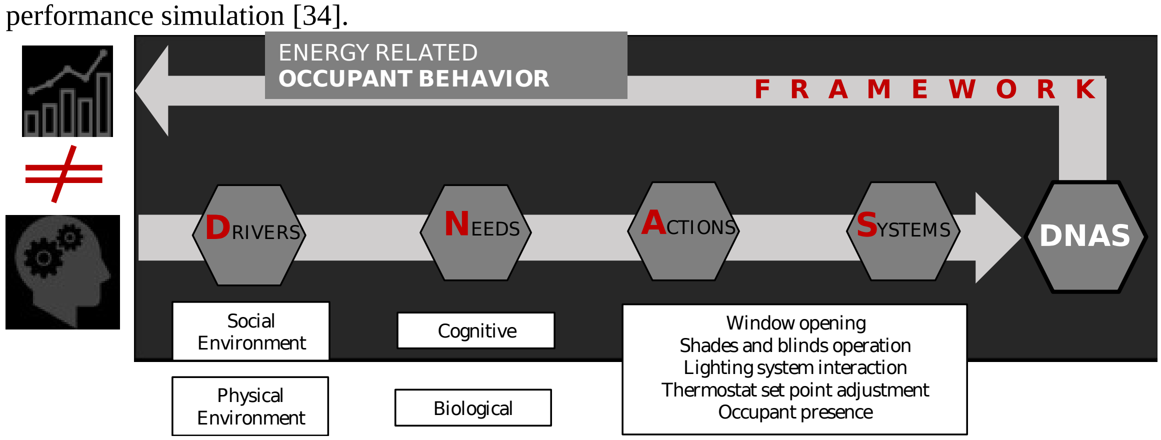


Figure 2. *The DNAS framework for energy-related occupant behavior*

2.3. The theory of planned behavior

According to the TPB (Figure 3), an individual's intention towards that behavior is the major predictor of one's behavior, and can hence be considered the direct antecedent (proxy) for behavior. In turn, behavioral intention is influenced by three key components: (1) attitude, (2) subjective norms, and (3) perceived behavioral control (PBC). The TPB developed by Ajzen [35] has been widely adopted by researchers in energy research and social sciences to analyze pro-environmental behaviors and target specific attitudes, subjective norms, and perceived behavioral control shaping behavioral intention and behaviors [36-41]. Confirming Ajzen’s theory, Kaiser and Gutshcer [42] were able to demonstrate that the three components of the TPB were capable of predicting up to 81% of the intention of a building occupant to perform energy conservation behaviors in homes. Similarly, Greaves, et al.'s [40] study of energy-related behaviors within a workplace determined that the TPB explained 61%–46% of variance in employees' intentions in engaging in pro-environmental behaviors, such as turning off their computers when leaving their desk, using video conferencing rather than traveling to meetings, and recycling at work.

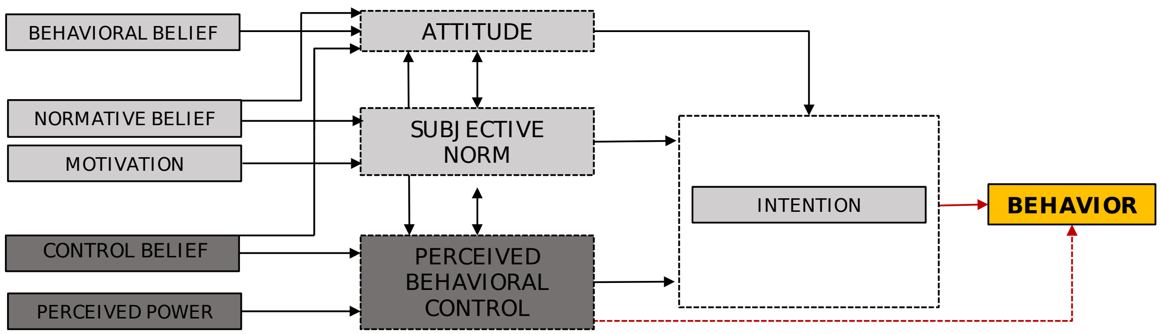


Figure 3. *The TPB is used to understand attitude, subjective norms, and perceived control influencing the exercised adaptive control in office buildings*

2.4. Strengths of the integrated framework

The new integrated framework has several strengths compared to each individual existing theory. These strengths lie in the selection of the most significant socio-technical components of energy-related behaviors from each of the three frameworks, as well as the synthesis of new variables reflecting the socio-technical nature of building energy use behaviors.

As pointed out by Adam Cooper, one of the prevalent limitations in the research field at this time is a lack of standardized ontology of socio-technical research. Disciplinary studies are typically based on either physical science-led (e.g., the DNAS, comfort theories) or purely social driven theories (e.g., the SCT, the TPB). A consequent gap in current research on building energy use behaviors is that technical surveys are deployed by using social survey methods, while social surveys rarely employ physical-environmental components or measures. As an example, the TPB ignores one's need to perform certain behaviors, but the DNAS framework has an explicit component to enhance it.

The DNAS framework explains energy-use behaviors (the actions having energy- and comfort-related effects on the control systems) as a direct consequence of personal needs, (e.g., thermal, visual, and acoustic comfort) compelled by a set of motivational drivers (e.g., temperature too hot, poor indoor air quality, lack of view from outside, etc.). However, data obtained through this linear approach is still based on physical components, which limit the degree to which social norms, group dynamics, or individual motivations can surface.

The TPB provides explicit components to improve the DNAS; i.e., how one's need to perform the behavior is mediated by social dynamics in the workspace, such as the perceived social pressure from co-workers and employers on how one should behave, or how the intention to share control is shaped by personal beliefs, habits, or the perceived power over the control systems.

The SCT connects with the DNAS framework and the TPB as the outermost layer organizing the dynamic interplay of environmental, personal, and behavioral factors (motivational drivers) of energy use behavior. This point reflects in the new framework in the hypothesis that people adopt certain behaviors to accomplish basic biological needs, but also with the influences of personal cognitive factors from the social environment (e.g., attitudes, social norms, perceived behavioral control further explained by using elements of the TBP) or physical environment (e.g., the actual access to the control systems as described in the specific element of the DNAS framework).

3. Research framework and questions

This research resulted in the development of an interdisciplinary research framework as an integration of the SCT, the DNAS framework, and the TPB (Figure 4). This study adopts the SCT as a general theoretical framework organizing the environmental (social and physical), personal (cognitive and biological), and behavioral factors having an impact on the human-building interaction within different climatic, cultural, and socio-economic contexts of the workplace. The DNAS framework is adopted to address the ontology of energy-related behavioral adaptations. A modification to the main TPB constructs—attitudes, subjective norms and PBC—is employed to explain the personal cognitive factors of behavior.

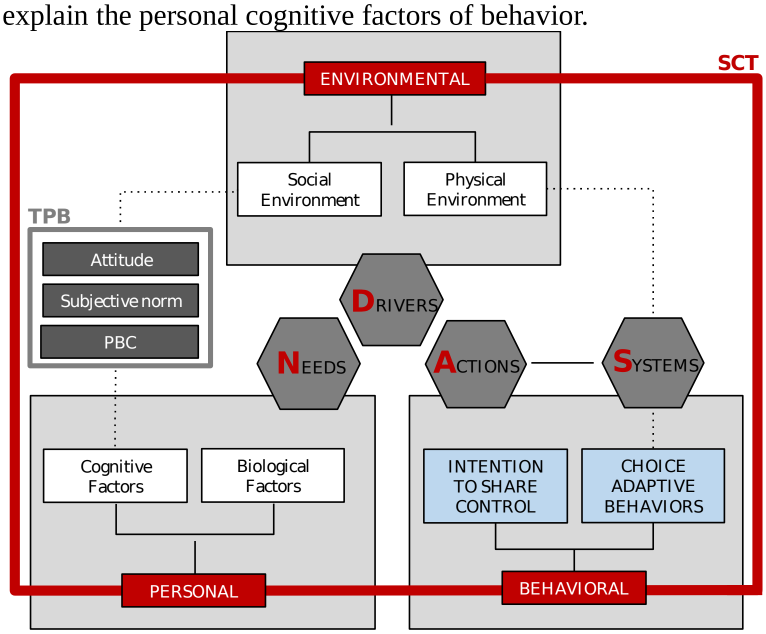
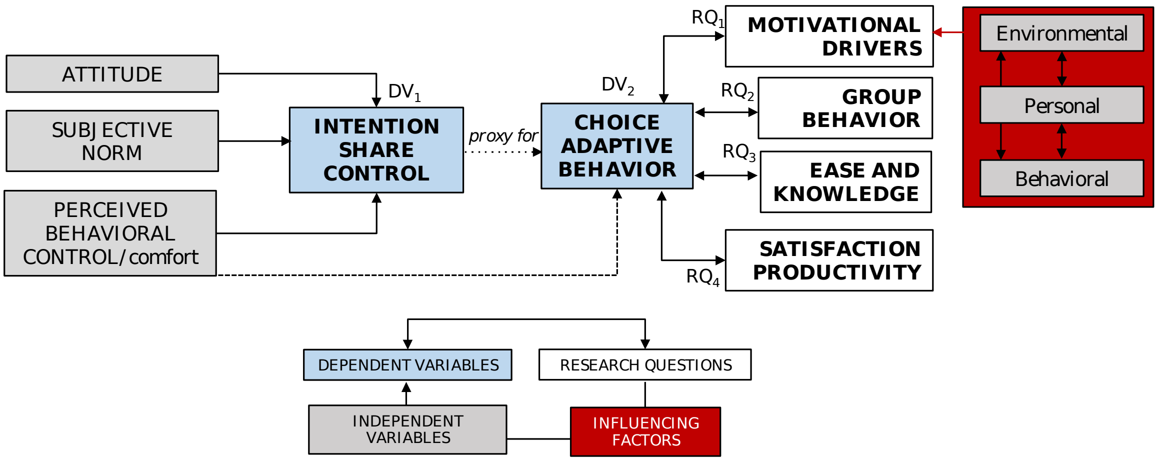


Figure 4. *The proposed interdisciplinary research framework, as an integration of the SCT, DNAS framework, and TBP.*

The research framework stands as the foundation for a survey instrument aiming to validate cross-country, data-driven knowledge on four research questions associated with the key learning objectives: motivational drivers (Section 3.1), group behavior (Section 3.2), ease and knowledge of control (Section 3.3), and satisfaction and productivity (Section 3.4). Two dependent variables (DV), the intention to share control (DV_1) and the choice of adaptive action (DV_2) are selected to explain the aspects of energy-use behaviors under investigation (Figure 5).



F*igure* ***5.*** *The proposed interdisciplinary research framework connected to the four research questions investigated through the survey instrument.*

3.1. Motivational drivers

Traditional research on energy-related occupant behavior in office buildings has primarily focused on the understanding of cause/effect mechanisms driving human interaction with the building systems and envelope to optimize energy consumption and comfort. Such approach explained motivations (drivers) of behaviors [43-45] by establishing correlations between specific observable (and monitored) variables and a particular behavior under observation (e.g., opening a window, turning on/off lights, and operating thermostats and shades). These variables typically include indoor and outdoor environmental (e.g., indoor/outdoor air temperature, illuminance level, CO2 concentration), contextual (e.g., time of the day, day of the week), and personal traits (gender, age, and user profiles). Recently, models accounting for influential contextual factors such as ease of control, freedom of movement, knowledge of technology, and usability factors are discussed within the building engineering community [10, 11, 15, 16, 23]

3.2. Group behavior

A previous study [46] stressed that additional knowledge on individual adaptive behavioral patterns and motivational drivers is especially needed for the office environment, where the interaction with building control devices to establish individual's comfort conditions is negotiated in social networks, and because monetary incentives for engaging in pro-environmental behaviors are negligible compared to residential spaces. Staddon, et al. [47] confirmed that social norms and group dynamics within the workplace are significant variables influencing employees' motivation to interact with the building control systems. Staddon, et al. [47] highlighted how information on employees' motivation on saving energy, and the influence of subjective norms, can serve to create intervention programs regarding energy use in the office spaces. According to Ajzen [48], subjective norms are the perceived social pressures from a meaningful reference person or group and/or beliefs about how these "significant others" believe one should act in a given situation

[49]. These highlights open to meaningful applications of our proposed research framework. For "significant others," our research refers to the "perceived social pressure" of performing an adaptive behavior from specific reference person (e.g., employer or building manager) or group of individuals (i.e., co-workers).

3.3. Ease and knowledge

According to Ajzen [35], PBC is outlined as “the perceived ease or difficulty of performing the behavior” in a specific situation. As illustrated in Figure 3, PBC is a function of control belief and the perceived power of the control. In the TPB model, PBC has both direct influences on behaviors and indirect influences on behaviors through behavioral intentions.

Based on the TPB, Chen and Knight [19] investigated how energy concerns influence employees’ intentions to conserve energy at work through the intervention effects of attitudes, PBC, and injunctive norms. Experimental tests have been conducted by Schweiker and Wagner [50] in order to gain insights into the effect of the perceived control level on negotiated behaviors in the working environments. Results demonstrated that the number of people sharing the working space negatively affects perceived control, and a lack of perceived control negatively influences the attainment of neutral comfort temperatures. Other researchers [41] demonstrated that the role of PBC indirectly influences energy use intensity and the intention to reduce it. Contextual and environmental factors affect perceived control as well. These include, but are not limited to: architectural morphology (e.g., open-plan, shared workspaces compared to private offices, proximity to windows and depth of plan spaces, presence of operable windows and shades, type of HVAC systems) [10, 45], building design robustness [51, 52], usability of control systems [53-55], social norm, group interaction [19, 56-61], personal and cognitive traits (i.e., perceived behavioral control, behavioral intentions, energy saving attitudes) [19, 35, 46, 62–64], and motivational drivers [43, 65-68]. Langevin, et al. [16] observed that behavior sequencing of adaptive actions in office buildings is a complex phenomenon, where multiple behavioral adaptations are sometimes available, and certain interactions are subject to contextual and social constraints instead. The longitudinal study conducted by Langevin, et al. suggested the most easy-to-use building controls tend to be chosen first, but multiple behaviors may be taken together as well, encouraging future work to explore behavioral determinants of ease and knowledge of building controls in offices of varying scale, conditioning strategy, and climatic context.

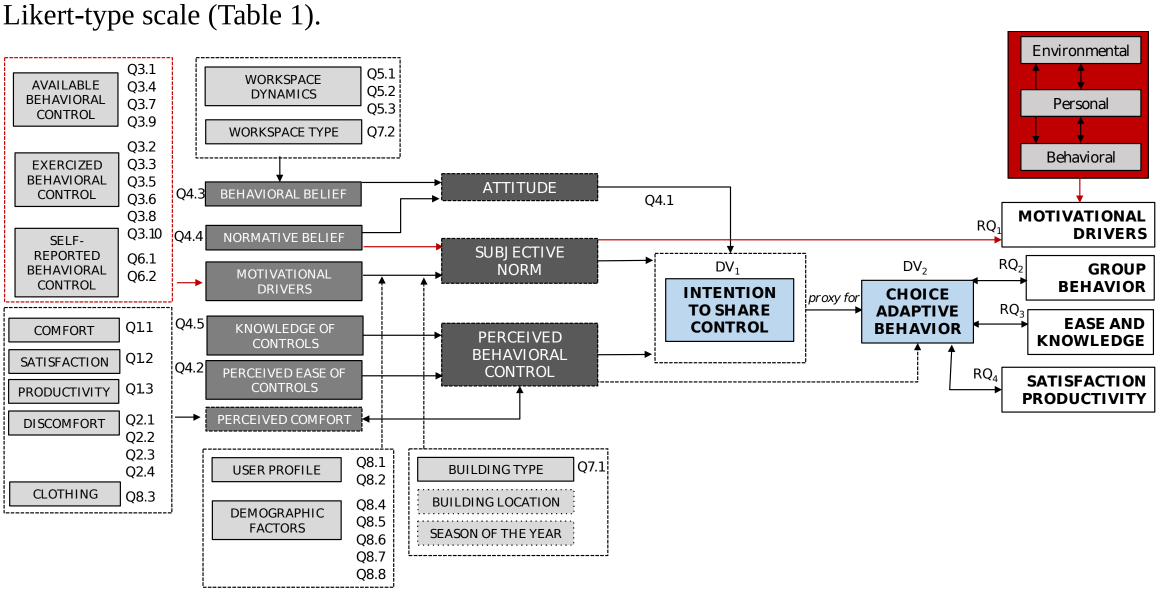
3.4. Satisfaction and productivity

Key components of the human-building interaction are based on the concepts of perceived comfort, satisfaction, productivity, and control over indoor environmental condition [16]. As an example, occupants having higher perceived control over the indoor environment have been observed being typically more satisfied (85%) than occupants who have not [10, 19, 50, 69]. Temperature control is one of the top features considered to be an important part of an efficient workplace; it is also the feature with the highest reported satisfaction [17]. For instance, the ability for individual workers to control the space temperature at their workstation has been shown to improve individual productivity by 3% to 36% [17]. However, choices of adaptive behaviors can also be perceived as a stressor. Studies of behavioral selection [14] demonstrated that the greater the number of behavioral options, the more difficult the task of selection. This mechanism induces to a reduced number of choices taken; accordingly, people tend to be more dissatisfied with the choices they have made, provoking a vicious circle of demotivating effect. Prohibiting actions or persuading people too much can be perceived as constraints, resulting in a desire for what has been banned or restricted, or even a repulsion towards to the persuading message [15]. As a generalization, to the extent users perceive positive realization of exercised control to ensure comfort conditions, their satisfaction with the indoor environment is guaranteed [13].

4. Questionnaire design procedures

Based on the proposed research framework, a survey questionnaire was designed consisting of 37 questions. The online survey was designed to investigate how social-psychological and demographic factors (i.e., independent variables) are related to occupants' behavioral intention in sharing the control systems (i.e., dependent variables) and identify occupants' choice of adaptive actions from a group of occupants by analyzing the statistical inference of the estimated parameters and the relative importance of each of these factors. Additionally, the survey results are expected to provide important social-psychological (e.g., group norms) findings to building efficiency solution and simulation modeling by considering both building technology and social context. The survey was designed to collect responses from the targeted administrative staff and faculties among 14 universities and research centers across four continents (America, Asia, Europe, Australia) and six countries (USA, China, Italy, Hungary, Poland, Australia).

The survey was conducted in three university institutions in Italy and in one university in the USA. The survey is currently open in several other countries (USA, three institutions in Poland, Hungary, Australia, and China). The survey is anonymous and no personal identification has been/will be collected. Each survey response was/will be recorded in the Quatrics software together with the date of compilation and geographical coordinates. Every survey question in the questionnaire represents one or more independent variables to articulate the 37 measures of the investigation (Figure 6). Two additional variables (building location and season of the year) can be directly inferred from the survey without compromising data privacy issues. All measures except for control variables are estimated by participants' responses to the items with a five-point Likert-type scale (Table 1).



F*igure 6. The proposed questionnaire to measure the research questions, consisting of 37 questions connected to dependent and independent variables.*

Table 1. *The proposed questionnaire addressing the measure of 37 variables plus two additional variables inferred from the survey responses.*

	Variable	Variable ID	Measure
1	Comfort	Q1.1	Comfort Scale
2	Satisfaction	Q1.2	Likert Scale
3	Productivity	Q1.3	Likert Scale
4	Thermal Discomfort	Q2.1	Control
5	Visual Discomfort	Q2.2	Control
6	Acoustic Discomfort	Q2.3	Control
7	IAQ Discomfort	Q2.4	Control
8	Clothing level	Q8.3	Control
9	**Intention**	**Q4.1**	**Likert Scale**
10	Behavioral Beliefs	Q4.3	Likert Scale
11	Normative Beliefs	Q4.4	Likert Scale
12	Knowledge	Q.45	Likert Scale
13	Ease of Control	Q4.2	Likert Scale
14	Role	Q8.1	Control
15	Occupancy	Q8.2	Control
16	Age	Q8.4	Control
17	Gender	Q8.5	Control
18	Culture	Q8.6	Control
19	Geography	Q8.7	Control
20	Education	Q8.8	Control
21	Window	Q3.1	Control
22	Blinds/shades	Q3.4	Control
23	Thermostat	Q3.7	Control
24	Lights	Q3.9	Control
25	Windows opening	Q3.2	Control
26	Windows closing	Q3.3	Control
27	Blinds/shades opening	Q3.5	Control
28	Blinds/shades closing	Q3.6	Control
29	Thermostat adjustment	Q3.8	Control
30	Lights on/off	Q310	Control
31	Adaptive behavior (hot)	Q6.1	Control
32	Adaptive behavior (cold)	Q6.2	Control
33	Density	Q5.1	Control
34	Group Negotiation	Q5.2	Control
35	Group Norms	Q5.3	Control
36	Building type	Q7.1	Control
37	Workspace type	Q7.2	Control
38*	Building location	N/A	Control
39*	Season of the year	N/A	Control

**Inferred from survey response*

4.1. Measures

4.1.1. Motivational drivers

By adopting SCT as an extension to the DNAS framework, this section attempts to explain (RQ_1) motivational drivers for adaptive behaviors—such as opening and closing windows, operating blinds and shades, adjusting thermostats, and turning on and off artificial lightings—in shared office settings. These motivational drivers can be further explained as a function of the available behavioral control (Q3.1, Q3.4, Q3.7, Q3.9), exercised behavioral control (Q3.2, Q3.3, Q3.5, Q3.6, Q3.8, Q3.10), and self-reported behavioral control (Q6.1, Q6.2), as well as user profiles (Q8.1, Q8.2), demographic factors (Q8.4-Q8.8), building type (Q7.1), location, and season of the year.

4.1.2. Group behavior

By using elements of the TPB, this study aims to explain (RQ_2) how behavioral beliefs (Q4.3) and normative beliefs (Q4.4) in the working environment, as the perceived social pressure from coworkers and employers on how one is expected to act in the workspace and how decisions are made to negotiate and share controls, relate to the intention to share control (DV_1) and hence the choice of adaptive actions (DV_2). This evaluation can be applied for workspaces that consist of different layouts (Q7.2) and dynamics (Q5.1-Q5.3).

4.1.3. Ease and knowledge

By using the PBC element of the TPB, this study attempts to explain (RQ_3) how the intention to share controls (DV_1) and the choice of adaptive actions (sequencing of available behavioral actions) (DV_2) during the heating and cooling seasons are related to the perceived ease (Q4.2) and knowledge (Q4.5) of how to interact with the building control systems. This correlation can be further explained as a function of diverse user profiles, demographic factors, and building characteristics.

4.1.4. Satisfaction and productivity

By using some extended elements of the TPB, the study attempts to explain (RQ_4) how the intention to share controls (DV_1) and the chosen adaptive actions (DV_2) are correlated to perceived comfort (Q1.1), satisfaction (Q1.2), productivity (Q1.3), sources of discomfort (Q2.1-Q2.4), and amount of clothing (Q8.3) during the heating and cooling seasons. These correlations can be further explained as a function of distinct user profiles, demographic factors, and building characteristics.

4.2. Sampling strategy and participant selection

The sample size is critical to consider in questionnaire design to avoid bias in results. Response rates can be kept high by providing respondents with some incentives that motivate them to fill in the questionnaire. To encourage participation, this study provided respondents with incentives such as monetary awards [105] and gift certificates [106]. Ethics protocols and privacy issues for handling human subject data have been approved in all participated universities.

The target of this survey is administrative staff, faculty members, and students regularly occupying their work spaces. Occupancy rates of this targeted sample may not largely differ from occupancy rates of typical commercial office buildings (9 am to 6 pm work schedule). Several occupancy patterns may vary depending on the organizational role. The study assumed faculty members will leave their offices to teach classes or to supervise students and managers will attending meetings, and that both students and researchers similar are similar to regular employees, etc.

A different aspect to consider is the perception of group dynamics and social norms, where the academic-research environment may play a different impact on employee's perception of how to behave in a certain situation (organizational roles, hierarchy, perceived pressure, etc.). These are aspects worthy to discover in further applications of the designed survey instrument.

4.3. Mitigation strategies

Self-reported questionnaires have often been criticized for providing circumstantial results [69, 70]. Occupants may report, for example, what they *think* they will do rather than what they *actually* do in practice. Moreover, survey responses related to perceived comfort, satisfaction, and productivity could be biased from factors such as weather, IEQ, and stress level, which may vary day by day [18, 71, 72]. However, it is a common practice to converge self-reported data with actual energy-saving data, or measured environmental parameters, in order to reveal important underlying drivers for behavior [70, 73-75]. For the analysis of these questions, this study will adopt a similar mitigation strategy. As an example, survey responses on self-reported perception over the indoor environmental parameters (e.g., indoor temperature, air quality, illuminance level) will be paired with meteorological data (e.g., outdoor temperature, relative humidity, solar radiation on the horizontal level) to determine the possible influence of external climate conditions on comfort, satisfaction, and productivity. Meteorological data are available from weather stations in the closest proximity of the geographical coordinates associated with each survey response.

4.4. Translation guidelines

The survey instrument, originally developed in English, is translated into national questionnaires, in diverse languages (Italian, Polish, Hungarian, Chinese). A translation guideline protocol has been developed and followed to ensure equivalence across languages. Semantic, conceptual, and normative equivalence of survey questions is guaranteed by re-translating survey questions back into English before finalizing translated versions, by following a double translation process (DTP) [76], one of most adopted translation processes for survey questionnaires (Figure 7):

a) **Preparation step.** Two bilingual translators for each language are identified. Elements of the english original version (EOV), which might be problematic to translate to the target languages due to any reason (terminology or differences in culture or built environment).
b) **First translation**. The EOV is translated by the first translator into each of the four target language versions (TV): Italian, Polish, Hungarian, and Chinese.
c) **Second translation.** The second translator took the results from the previous step (TV) and independently translated the survey questions back to the original language: the English translated version (ETV).
d) **Comparison step.** The two versions of the survey questionnaire in the original language (EOV) and in the translated version (ETV) are compared for inconsistencies, mistranslations, meaning, cultural gaps, and lost words or phrases. If any differences are found, translators are consulted to find out why this occurred and how the instrument can be revised.
e) **Verification step.** Both the EOV and ETV of each of the four target languages are compared and checked for inconsistencies. A few iterations of this step (back to Step a) occurred to ensure proper translation before the final TVs have been approved.

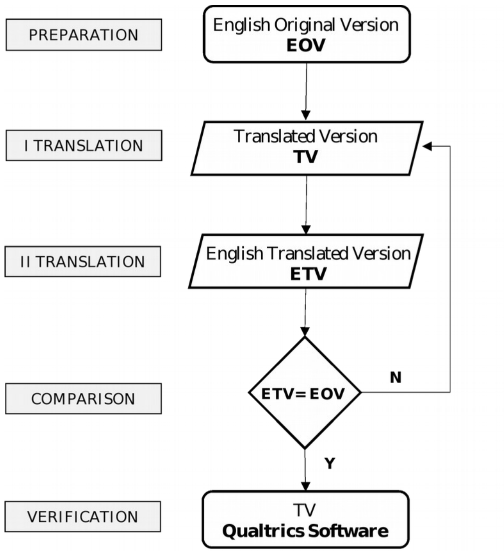


Figure 7. *Workflow of the translation phase*

At the positive conclusion of the verification step, the Italian, Polish, Hungarian, and Chinese TVs have been implemented into the online Qualtrics software. Individual links to the questionnaires have been created and sent to participants in each country. Future papers will present and discuss the survey results and findings.

5. Discussion

The significance of including interdisciplinary studies in the understanding of the human dimension of building energy usage and consumption patterns was recognized by a set of distinguished scholars [37]. These experts communicated their views for integrating the fields of anthropology [77], behavioral studies [78–80] into the energy research agenda. Psychologists such as Stern [81, 82] argued that human behavior must be accounted for in the field of energy research. Stern also claimed that separate discipline lenses alone could not provide the complexity of knowledge needed for understanding and influencing human interactions with energy systems. Rather, integrative solutions and insights gained from trans-disciplinary expertise are needed [83].

5.1. Benefit of interdisciplinary research

Interdisciplinary research is critical to fluidly merge discipline-based knowledge that has not been combined in previous research. This interdisciplinary research enhances a holistic problem-solving conceptualization able to tie the human and energy systems into an innovative (and superior) research space. Within this enlarged knowledge-based arena, researchers can develop theories and models of the human-energy interactions phenomena that are more effective for designing interventions to support energy-related behavioral changes. This work can also provide more accurate energy resource and building control usage predictions and more affordable, robust, and efficient energy and building control services—all to the benefit of building occupants, building owners/operators, and the environment.

The benefits of socio-technical interdisciplinary research in achieving energy savings in buildings have been discussed by Uiterkamp and Vlek [84], who analyzed outcomes of practical case studies for which behavioral and environmental interventions have been most effective. This work highlighted the fact that collaborations can tackle both technological and socio-cultural disciplinary issues together. Steg and Vlek [85] and Abrahamse, et al. [12] further confirmed the effectiveness of two-way communication exchanges among environmental scientists and psychologists.

Research outlined in this paper goes beyond previous research, creating a framework and research instrument that establishes a common language and platform for cross-country comparisons of socio-cultural and circumstantial aspects of energy-related behaviors in the building sector. Given the complementary results on energy-related behaviors adopted by building physics (the DNAS framework) and social psychological theories (e.g., the SCT and the TPB), decision-makers may benefit from a more interdisciplinary research framework enabling communication exchange and co-learning between disciplines throughout the entire building life cycle.

5.2. Advances from interdisciplinary research

By conducting an interdisciplinary, cross-country survey, many questions of the energy and social science fields can be answered, providing advances in the sensing, modeling, simulation, and regulation for enhancing future human-building interactions.

5.2.1. Sensing advancements

Sensing building and human data is the new trend in building energy efficiency. However, innovative sensing techniques for occupant behavior in buildings should not merely focus on monitoring individual behaviors and influencing factors. Reporting the plausible general behavior of a group of people might be more significant than describing personal and isolated behaviors. Accordingly, this project focuses on developing observation methods of collective and social conventions shaped by geographical context, culture, and norms that are driving occupant behavior. These observation methods are crucial to determining behavioral patterns that have varying consequences for building energy consumption and indoor environment comfort. The questionnaire presented here can be considered as an optimal instrument for the discovery of a layer of social, contextual, and group interaction constructs related to driving forces and individual motivations [15, 19, 39, 40, 64, 70, 86-92]. Directly questioning subjects might overcome the constraints of physical sensing techniques in gathering insights of multiple behavior interactions (i.e., the order of actions typically performed by the occupants to restore or bring about comfort conditions). Another issue to consider is the trade-off between data accuracy and scalability for achieving high-impact results and bridging the credibility gap of energy efficiency in buildings.

5.2.2. Building operation advancements

In the commercial sector, researchers [93] suggested that behavioral-based programs do not necessarily need to target every office occupant to "use less energy." Indeed, the data-driven knowledge on actual building control and operation, to be collected and derived from this survey, targets to facilitate the energy managers to optimize building automation systems (BAS) and energy management and control systems (EMCS), the portfolio managers to incorporate required comfort driven retrofits into business investment options, or the policy and decision makers to configure programs able to drive more adoption of efficient building systems utilization. Advancements in BAS and EMCS include the possibility of enabling higher levels of perceived personal control. Higher perceived personal control allows users to solve personal comfort-driven tasks/actions at the zone level (human-centered actual dynamic/transient [41, 131]) and increase IEQ satisfaction without influencing the overall comfort level/perception (centrally designed neutral/static homeostasis) and energy efficiency (avoiding system over running) at the building scale. Further, knowledge collected through the survey can allow strategies for negotiating comfort conditions among occupants of adjacent building zones.

5.2.3.Modeling and simulation advancements

The DNAS framework represents a common information exchange ontology for a standardized modeling approach of energy-related occupant behavior. Current applications of the DNAS framework are broad, including building energy modeling and simulation, building design, development of codes and standards, and the support of building performance policy decisions [33, 34, 94]. Advances in occupant behavior modeling in building performance simulation are accommodating more advanced inputs compared to traditional approaches to describing building occupants as deterministic schedules that play a mechanistic role in the interaction with building technologies [8]. Extending the DNAS framework to include data-driven knowledge gathered from the survey can facilitate the integration of contextual factors of behaviors into current behavioral models. In the long term, this improvement promotes comparison, sharing, and validation of occupant behavior data-driven models among disciplines outside the energy arena. The availability of more interdisciplinary occupants' data-driven knowledge—and behavioral models—to simulate varying parameters associated with specific building features or climate can further provide insights into actual energy performance fluctuations in buildings. This will help to bridge the accuracy gap between the predicted and actual human-building interaction, and, hence, energy performance, consumption, and comfort [9, 54, 95, 96].

5.2.4. Policy advancements

Researchers [21] have been arguing for the energy policy arena to adopt a more integrated socio-technical approach to building efficiency analysis. They have emphasized that energy consumption (especially in low-carbon buildings) has robust correlations with the attitude and engagement of the energy users [97]. Stoknes [98] showed the enabling role of social psychology in understating public concerns and their perceived importance for climate change and therefore supporting the development of more effective climate policies. The discovery and understating of the interlocking nature of technical, cognitive, and behavioral aspects, such as the energy users' knowledge, ease of use, and intention to use specific technologies, became critical for policy makers and practitioners in the development of energy efficiency practices, codes, standards, and programs. Up to recent times, evaluation of technology adoptions, the convolution of energy usage decision-making processes, as well as the human dimensions of energy use emerged as neglected topics in the energy technology and policy fields [99]. Integration with behavioral programs and energy efficiency scenarios including social-scientific approaches (i.e., evaluating the socio-economical-technical dynamics fostering or impeding the adoptions of building energy technologies and controls) [100, 101], and its environmental impacts, are just examples of how the policy community can profit from this research to unlock the disciplinary boundaries of energy efficiency studies in the building sector.

5.3. Barriers for interdisciplinary research

The barriers preventing social science and building physics to become the pillars of the integrated energy research agenda towards a low-carbon future have been largely discussed. A variety of perspectives from the existing literature represent a significant informative source for engaging with some of these central themes. Barriers impeding the practical development of interdisciplinary research and programs in the field were discussed by Lutzenhiser [102]. Constraints are represented by the limits of the building sector and building energy efficiency regulatory frameworks for evaluating human-sided vs. technical-economic energy efficiency measures, and the professional modus operandi of social scientists, engineers, architects, economists, anthropologists, policy makers, government bureaucrats—including diverse theoretic and empirical methodological orientations and modes of expression.

Other barriers derive from a lack of technical knowledge of the psychological and cultural, rather than purely physical, phenomena regulating the occupants' physiological adaptation in indoor environments from the energy and social science research, respectively. Diverse theories have been historically applied by these two disciplines to explain and understand human behavior. In the energy research field, the narrow disciplinary approach to energy analysis and forecast has been recognized as one of the key barriers for energy programs to meet their anticipated energy saving/efficiency targets.

Only recently has the energy and building technology community started to acknowledge that buildings don't use energy, but occupants do [80], shifting the focus of the energy efficiency research and policy development towards social sciences. On the other hand, psychological research, when included in energy policy-making processes, has been diagnosed by scholars such as Cooper [104] as having limited impact due to its qualitative rather than quantitative analysis, focusing on mental states and processes, while failing to understand the significance of physical properties and measurements associated with building energy performance.

One of the solutions claimed here is not simply to include social science as an afterthought in a physical context, but rather as an "equal partner" [105]. In the broader perspective, as argued by Galvin [106], the priority must be given to interdisciplinary research on energy consumption, which conveys the knowledge, methods, and metrics of building physics, economic, policy-making, and psychological and social science research altogether.

Other barriers to bridging the energy and social sciences relate to a lack of consistency in terminology between the social science and engineering disciplines when referring to motivation, habits, and behaviors in general. While the common language of physics is used to understand the quantitative laws of energy and its dynamics, social scientists tend to use both qualitative theories and quantitative methods to describe energy-related behaviors and how energy marks socio-cultural relationships.

As pointed out by Stephenson [107], an understanding of physics and social science theories can be increased in the social and energy research areas, respectively, creating a collaborative space that may benefit, as in our case, building energy research. If the assumption is that social science practices and advices can foster the achievement of a low-carbon transition in the energy sector, as showcased by Cooper [104], these solutions must not just target policy makers, as argued by Stern [108]. Similarly, Mallaband, et al. [109], offers an alternative standpoint to Cooper's hypothesis that social scientists should adopt physical energy terms to be policy relevant. In the building sector, this work shows that one of the remaining challenges is how insights can be put into the service of a wider spectrum of stakeholders influencing the "human factor of energy usage."

Throughout the entire building life cycle, interdisciplinary research outcomes must be disseminated to building occupants, operators, energy managers, building technology vendors, utilities, and local governments in addition to the policy makers.
Given the complementary visions provided by physics and psychology (as argued by Spreng [110]), this study shows that significant impacts may result from a mutual increased capacity within both the energy and social sciences to enable communication exchange and co-learning between disciplines. Thought it is true that realistic energy policy should not be established based only on social data, as discussed by Mazur [111], it is equally true that energy data alone have failed to provide full-scale meanings of the energy use phenomena. The proposed integrated framework, as synthesized from multiple interdisciplinary theories, and the correlated questionnaire survey as a research instrument, can foster interdisciplinary data gathering and impactful applications over the entire building lifecycle.

Another barrier to consider is that currently used frameworks and schema representing occupant behavior for simulation are developed based on quantifiable physical parameters driving the behavioral adaptation phenomena to the indoor environment (IEQ thermal and visual comfort related). It is challenging to quantify and integrate social variables into these frameworks, and, more importantly, to convince engineering practices to incorporate those into energy simulation scenario. Designing robust models and efficient control logics that achieve behavioral-based energy savings while ensuring occupants satisfaction in office buildings remains an open problem.

Collecting research across international boundaries is crucial in energy and social science fields for understanding occupant behavior and achieving optimal energy usage, but it is challenging to obtain due to cost and language barriers. Innovative human-building related investigations must consider the interdependencies and complexities of efficient energy use and technology adoption in buildings. The manifold aspects of occupant behavior play out in different building types and geographical contexts. Given the critical nature of the climate change challenges and emission reduction goals, any study merely producing new knowledge through discrete research is doomed to be unsuccessful in terms of tangible impacts. Rather, such fundamental knowledge needs to be translated into interdisciplinary frameworks and theories, which are understood and shared among disciplines, in a way to drive instrumental solutions, actions, techniques, and technologies having measurable effects and valuable efficacy. One of the biggest challenges remains how to translate sectorial insights into exploitable action plans in ways that enhance the efficacy or uptake of solutions, measures, and directives in the context of such complex issue. Ensuring semantic, conceptual, and normative ethical consistency between translations of the questionnaire defines the key intrinsic risk and challenge of this cross-country survey.

6. Conclusions

This study introduces an interdisciplinary framework and cross-country survey project based on the synthesis of building physics and social psychology theories explaining human-building interaction in buildings. The DNAS framework is chosen for rationalizing motivations of energy-related adaptive behaviors in buildings. The SCT is selected as a general theory explaining cognitive processes of human behavior in social contexts. Following these two theories, the survey attempts to (1) improve understanding of occupants' environmental, personal, and behavioral motivational drivers leading occupants to interact with the control systems in socially dynamic environments such as office settings. Additionally, based on the elements of the TPB, efforts are dedicated to investigating how (2) subjective norms, as well as group negotiation and workspace dynamics influence the group interaction with control systems—and vice versa—and how (3) adaptive control behaviors (order of actions) are correlated to the perceived behavioral control, and the (4) perceived comfort, satisfaction, and productivity. The research framework and survey instrument were developed to overcome key barriers by uncovering innovative, data-driven knowledge on the human-building interaction in the office setting.

The survey instrument is an online questionnaire designed to collect responses from targeted administrative staff and faculties among universities and research centers across four continents having heterogeneous cultural contexts and climate regions. A comparison among different countries, cultures, and climates through a variety of office settings aims to provide new insights into group behaviors such as an intention to share control with others, individual motivational drivers of adaptive actions, and order of adaptive actions. A future follow-up paper will present and discuss the survey results. Further advances in research need to be fostered towards the development of effective, informative resources to educate a broad spectrum of stakeholders in an interdisciplinary arena, including building occupants, designers, energy modelers, social scientists, and policy makers.

Going forward, efforts to strengthen and update multidisciplinary and international relationships and networks will be continuously nurtured; both within the Annex 66 research arena as well as the industry communities, such as the ASHRAE Multidisciplinary Task Group on Occupant Behavior in Buildings. The final goal is to drive better empirical findings towards the development of market actions and international codes and standards.

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