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On Occupant Behavior and Innovation Studies Towards High Performance Buildings: A Transdisciplinary Approach

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Abstract: With ever-increasing population and urbanization, it is crucial to decrease energy density in the built environment without sacrificing occupants' comfort and well-being. This requires consideration of technological developments along with the human factor in order to achieve environmental and social sustainability. Two major contributors to the development of conceptualizations for human-centric technologies are behavior and innovation (B&I) studies. Behavior studies aims to explain individualistic or society-based dynamics of human behavior whereas the innovation studies focuses on social, economic, organizational, and regulatory dimensions and processes of inventive activity. If these studies are incorporated into the hardcore architecture and engineering disciplines with a transdisciplinary approach, the orchestration of occupant behavior and the innovative technologies would be possible, which in turn significantly enhance the comfort and energy efficiency in built environments. This paper aims to provide an overview of interdisciplinary dialog between B&I studies and underlines the role of their collaboration to leverage transdisciplinary research on human-building interaction for energy efficiency. The approach presented here is structured as a conceptual framework and named the 'socio-technical core' (STC). STC is to lead to more organic articulation of energy efficiency innovations with real life and pave the way for higher level of acceptance. In order to have a 'big-picture' for the well-accepted conceptualizations and the current status of interdisciplinary dialog, we provide a review of (B&I) theories and models along with network analysis of key concepts. Then we investigate the potential directions of future transdisciplinary efforts by discussing the influences of B&I studies to each other for application to energy efficiency studies. In order to put the analysis in a firm background, we provide a case study for thermostat, which can be considered as a product improved with B&I approaches during last decades. We also discuss the benefits of B&I based transdisciplinary research perspective by referring to few examples in literature and the points emerged in this study.

Keywords: energy efficiency; high performance buildings; human factor; behavior; innovation; network analysis; socio-technical; transdisciplinary; technology acceptance; smart thermostats

1. Introduction

By the year 2050, the world population is expected to increase more than 20%, and 66% are expected to be city dwellers. This means 2.5 billion more people will be living in urban areas and spending most of their time in buildings [1]. Buildings are already responsible for more than one-third of the global final energy consumption, mostly due to space heating/cooling, water heating, and other appliances [2]. This ratio tends to increase due to the fact that urbanization is the fastest in the regions where the need for space cooling is higher [3]. These facts make building energy efficiency to be one of

the key issues to be considered for achieving global resource sustainability. To avoid the devastating effects of climate change, International Energy Agency (IEA) suggests a decrease of 40% in energy density of buildings by 2050 [4]. Beside the role in resource management, buildings are also expected to offer better living conditions (e.g., comfort, health and productivity) and well-being to their occupants, as the ‘new habitat’ of humanity. Despite seen to be contradictory, the proposed interventions should augment resource efficiency without sacrificing occupants comfort in order to be sustainable and acceptable. For the sake of offering higher well-being, as well as physiological concerns, technologies and regulations should be in accordance with culture, norm and expectations of people. In other words, the goal of increasing building energy efficiency for environmental sustainability can only be realized with the innovations that are in harmony with human behavior.

The US Energy Information Agency (US-EIA) estimates the global yearly average of energy intensity for residential buildings is 88 kWh/m², whereas for commercial/academic buildings it is 198 kWh/m² [5]. While designing the high performance buildings (HPB) of the future, the main stream research focuses on technology-driven solutions like better insulation materials, green roofs, energy monitoring, advanced HVAC control, among others. On the other hand, there has been an increasing emphasis on the interactions between the occupants and energy systems of buildings during last decades. This is to facilitate the orchestration of human behavior and new technologies [6]. In this sense, behavior and innovation (B&I) studies have been proven to be relevant and instructive [7,8].

There is a large body of literature about human (occupant) behavior regarding to energy efficiency in built environments, which aims to explain individualistic or society-based dynamics of behavior. Behavior theories and models in this field are closely related to pro-environmental and eco-friendly behavior research. They established an understanding of human response to energy-related concerns (environmental impacts, social norms, economic benefits, etc.) and influencers of these concerns (comfort, desire, needs, symbols, etc.) [9]. Besides social-sciences-based theoretical efforts, studies referred as ‘behavior modeling’ aim to develop computational modeling based engineering practices to analyze, simulate and predict human behavior and its impact on energy consumption [10]. Innovation studies are focused on social, economic, organizational and regulatory dimensions and process of inventive activity [11]. This field represents an increasing attention to explain interrelationship between dynamics of consumer behavior and pro-environmental innovation [8], [12]. As expected, there are common attributes between behavior and innovation studies (e.g., norms, values and cultures). However, the decision-making processes regarding to energy efficiency interventions are explained with different approaches to behavior [13] and the innovation literature [14,15]. This makes it possible to establish an organic interdependency between these fields based on common attributes and hybrid conceptualizations. By doing so, we can achieve a better understanding of dialectic relationship between human factor and energy efficiency products and services in built environments.

Understanding of multidimensional issues such as the sustainability and proposing real-life solutions for them requires unorthodox strategies, which can be ‘approached’ by transdisciplinary studies [16]. There are no simple solutions for this quandary; instead effective strategies should be developed based on interaction between diverse disciplines as well as variety of actors: scientists, regulatory bodies, investors, among others. Accordingly, for the design, construction, and operation of energy efficient buildings, disciplines such as mechanical, electrical and civil engineering, computer science, urban sciences, architecture, as well as psychology, sociology, anthropology, law, and economy are needed to be considered in tandem. In line with these considerations, in this paper we discuss the current status and future perspectives of interdisciplinary dialog between B&I studies and highlight its potential benefits for the development of transdisciplinary research strategies towards better building energy efficiency measures.

Below, we introduce and discuss a conceptual framework, called “socio-technical core” (STC). We highlight the foundations of our approach and map the general strategy, as schematically shown in Figure 1. STC is composed of two-way exchange of concepts and methods between B&I literature and aims to translate needs and capabilities of research activities focused on human factor and building

systems to each other. Based on this approach, researchers and developers can tune and integrate their tools with the tone of better user experiences. This would make it more possible to go beyond the limits of technology-driven solutions for the design, construction and operation of HPBs and the corresponding systems. Beside its significant potential for research and development activities, the STC approach can also establish an understanding and help to develop tools for more effective relationships. This is possible among shareholders in a building ecosystem (like owner, architects, engineering design team, operation managers and occupants) as well as the policy makers and regulatory bodies. We note that the details and the fundamental aspect of STC can help to initiate a deeper transdisciplinary research methodology or framework, which can be discussed in a separate study in the future.

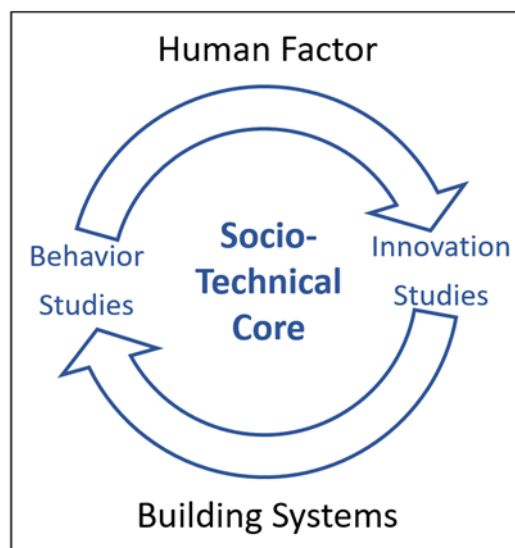


Figure 1. The conceptual framework for ‘socio-technical core’ (STC). It is based on a two-way conceptual exchange among behavior and innovation studies, which is to leverage interaction between research activities focused on human factor and building systems towards better energy efficiency.

Both B&I studies are active research fields. Occupant behavior literature, which is extensively reviewed independently, mainly discusses personal and societal determinants of behavior. Innovation literature, on the other hand, mostly deals with the market response and consumption patterns of eco-innovations. However, to our knowledge, there is no previous attempt which that discusses interdisciplinary dialog between B&I studies for the energy efficiency in built environments. There are only few studies benefiting conceptualizations and methodologies from both of these domains. In this paper, we start with providing a detailed review of B&I studies in Section 2, which is prepared using manual content investigation. In Section 3, we provide a network analysis of key concepts outlined in both sets of literature to evaluate the current status of conceptual interdisciplinary dialog between B&I. This analysis is based on the dataset extracted from Clarivate Analytics Web of Science (WoS) database. Based on reviews and analysis in previous sections, in Section 4, we discuss the benefits and potential directions of transdisciplinary research, which can facilitate the collaboration of B&I studies for higher level of energy efficiency in buildings. Our approach can provide insight for the human interaction of variety of building energy systems including operable window shades, HVAC system, lighting system, among others. In order to provide a clearer perspective, we exemplify our approach for the smart thermostats in Section 5. We provide an overview of our approach and the future research plans in Section 6.

2. Literature Review

In this paper, we focus on theories, models, and core concepts that will help us to put the B&I-related conceptualizations for energy efficiency in transdisciplinary context. We choose theories

and models that are well known as fundamental approaches, empirically proven, or previously tested for energy efficiency research in the literature. There isn't comprehensive bibliometric analysis of neither behavior nor innovation studies for building energy efficiency domain. Thus, we initiated our literature research with peer reviewed, widely-cited, and review-oriented papers of both research fields. Furthermore, we conducted a detailed keyword based search on the search engines of the outstanding journals for these topics (e.g., Sustainability, Energy Research and Social Science, Energy and Buildings). We also benefited our previous knowledge based on related work. We don't intend to provide a comprehensive review of B&I theories and models for all disciplines and with historical and contextual details. Instead, we aim to lay out the conceptual foundations of B&I literature focused on building energy efficiency and the interdisciplinary dialog between them.

2.1. Overview of the Behavior Science for Energy Efficiency in Buildings

Following the energy crisis in the mid-1970s, more attention was paid to physical and technological constraints of energy systems for the building energy efficiency applications. However, in a period of less than two decades, researchers have differentiated that the gap between proposed and realized energy savings is mostly due to behavior of building occupants and operators [17]. Initial efforts to get a better understanding of the human behavior for energy efficiency were focused on rational-economic and attitude-behavior models. Rational choice theory (a well-known version is proposed by Elster in 1986) is one of the leading conceptualizations of this school. This approach dominated the field for decades and mostly used to design mass information campaigns [18]. Also, utility companies supported these studies to understand variation in energy use among customers [19]. Following the increasing interest of social scientists, from the domains like behavioral economics, environmental psychology and sociology, anthropology, among others, energy efficiency studies became more human oriented. Norm-activation theory (proposed by Schwartz and Howard in 1981), theory of planned behavior (proposed by Ajzen in 1991) and value-belief-norm theory (proposed by Stern in 2000) are some well-known examples of such contributions [20]. These and other important models and theories of behavior are discussed in the following subsections.

As a result of increasing attention of social sciences, there is a large body of theories and models of human behavior regarding to energy use in built environments. Classification and comparison of models and theories used to understand energy consumption behavior of occupants are provided in [21,22]. The role and importance of these theoretical conceptualizations for building energy efficiency are further discussed in [23]. The contemporary approaches for theoretical investigation of energy-related behaviors of occupants are discussed in [24,25]. Also, a comparative and historical analysis of approaches to understand behavioral concerns of sustainable consumption is provided in [9]. Following the footsteps of these reviews, behavior theories and models can be grouped under four main branches: economical, psychological, sociological and integrated approaches. Economic theories and models consider energy as a meta of energy market and provide explanations for the consumption of it in micro- and macro-levels by taking advantage of very large literature developed for other markets. Psychology theories and models deal with decision-making processes of individuals in the light of their attitudes, knowledge, habits, economic concerns, among others. Sociological theories and models deal with common perception, symbols, acculturation and/or education of energy consumption. Integrated theories and models take advantage of approaches originated from different disciplines and synthesize them for a more comprehensive explanation of occupant behavior [9]. In the following subsections, we provide a brief review of each branch with the corresponding theories, models and core concepts. Figure 2 shows the tree of theories and models of each branch, which is highly fragmented due to the long historical background over more than 50 years. The corresponding concepts, theories, models, and the references for each approach are listed in Table 1. Note that Figure 2 and Table 1 should be used together for references and for the details of the abbreviations.

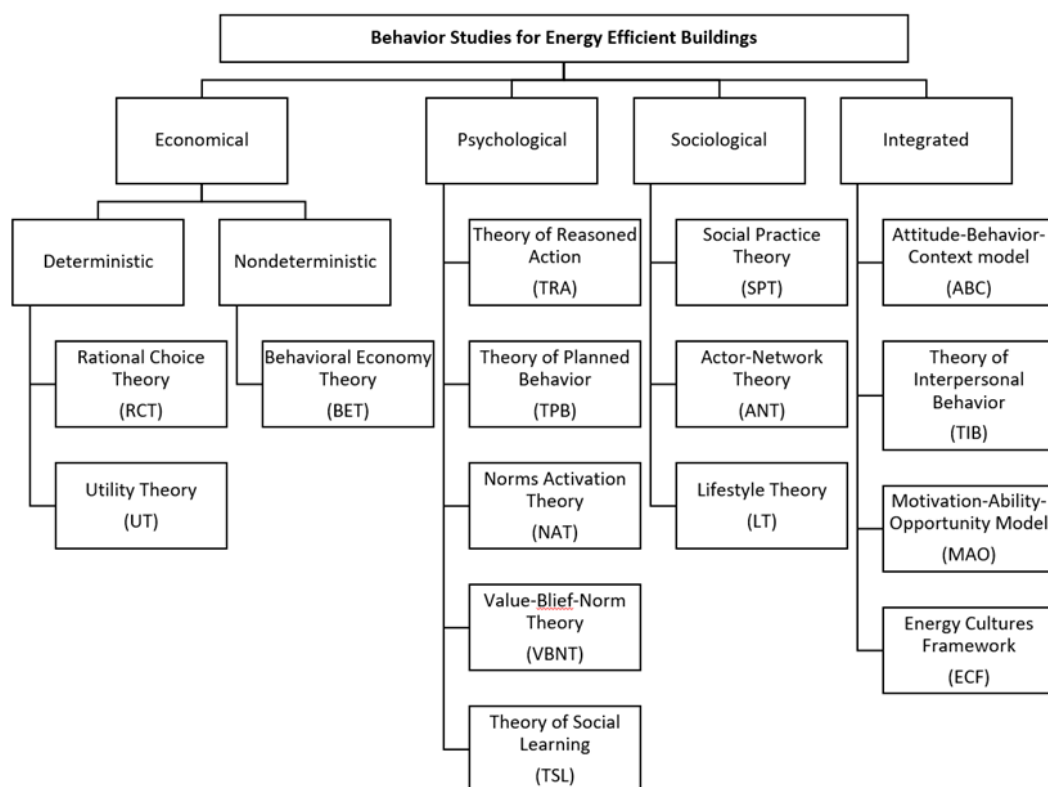


Figure 2. The tree of behavior theories and models from different disciplines related to building energy efficiency. Corresponding references are enlisted in Table 1.

Table 1. Summary of behavior literature for building energy efficiency. For abbreviations, see Figure 2.

Branch	Theory and Models	Important Concepts	References
Deterministic Economic Approaches	RCT, UT	rational choice, utility, desires, beliefs, evidence, benefit, outcome	[26,27]
Nondeterministic Economic Approaches	BET	behavior, desires, beliefs, attitude, value, resource constraints, knowledge, perceptions, contextual factors, rewards, feedback	[28–30]
Psychological Approaches	TRA, TPB, NAT, VBNT, TSL	attitude, norms, value, intention, evaluative beliefs, normative beliefs, motivation to comply, perceived behavioral control, awareness of consequences, ascription of responsibility, learning	[9,31–39]
Sociological Approaches	SPT, ANT, LT	practice, convention symbols, culture, performativity, routine, network, agents, lifestyle	[40–48]
Integrated Approaches	ABC, TIB, MAO, ECF	attitude, context, beliefs, norms, values, legacy, policy, habit, facilitating conditions, social factors, affective factors, motivation, ability, opportunity, lifestyle, system thinking, culture	[9,13,49–51]

2.1.1. Economic Approaches

Behavior theories based on economic approaches can be classified by means of their rationality approach regarding to dynamics of economical decision-making. One of these groups considers human behavior as a deterministic phenomenon and includes the rational choice theory (RCT) and utility theory (UT). RCT explains human behavior as to be a result of a decision making process which analyses the perceivable interrelationship among desires, beliefs and evidence, and choose between certain alternatives in a way to maximize benefits [26]. Similarly, UT settles on discrete choices of rational actor who is looking for the best fitting outcome, and so maximizing utility function [27]. However, these theories of rational choice approach are criticized to be ignorant regarding to variety in values and preferences; impact of past on attitudes and values; resource constraints (income, time, memory, etc.) and various opportunities of social life [28]. As a result of these critics, the other branch of economic approach, namely behavioral economy theory (BET), focuses on deviations from rationality of choices and reasons by taking advantage of concepts mostly from the field of psychology. EIA lists the main drivers of behavioral variability as inconsistent temporal framing, status quo bias, loss aversion, decision-making heuristics, salience effect, prosocial behavior and permanent income hypothesis paralysis [29]. For individuals, knowledge, perceptions, contextual factors (like pay-off structure), rewards, and feedback are proven to be relevant tools to design and deploy economic behavior change interventions whereas the effectiveness of each is seen to be case specific [30]. BET is more sensitive to temporal and spatial variations in societal and individualistic factors and so provides more adaptable perspectives to discuss economic behavior and its change for energy efficiency.

2.1.2. Psychological Approaches

Approaches originated from social and environmental psychology comprehensively discuss the influencers of human behavior. Being one of the early theories, the theory of reasoned action (TRA) introduced the concepts of *'attitude towards behavior'* and *'subjective norms'* as antecedents of *'behavioral intention'*, which is the only driver of behavior [31]. TRA is extended over the years by including concepts of *'evaluative beliefs'*, *'normative beliefs'*, *'motivation to comply'* and *'perceived behavioral control'* [32,33]. A comprehensive and extendable version of the approach, named as the theory of planned behavior (TPB), has turned out to be one of the most widely applied and well cited theories of behavior studies in a large set of domains including building energy efficiency. Being applied for the several aspects of environmental sustainability, it is commonly used to understand role of behavior for mitigating climate change [34]. It also provides insights to understand influences of organizations [35] and country cultures [36] on energy-related behaviors of people. Figure 3 shows the interdependence of the concepts included in TPB: behavior is mainly determined by *'intention'* that is under the influence of attitudes and subjective norms (as in TRA) in parallel to their *relative importance*. Moreover, attitudes are driven by *'beliefs about outcomes'* and *'evaluation of outcomes'* and *'subjective norms'* are driven by beliefs about what others think. An important determinant included in the TPB is *'perceived behavioral control'* which means the perceived easiness or difficulty of a specific action by the actor. It influences behavior either directly or via intention or subjective norm.

The two other well-known theories of social psychology, norm activation theory (NAT) and value belief norm theory (VBNT). These theories focus on moral and normative contexts of human behavior and open to practical studies (see Figure 2). NAT replaces the importance of intentions with *'personal norms'* (moral self-obligations) and proposes the concepts of *'awareness of consequences'* and *'ascription of responsibility'*, which are powerful influencers of each other [9]. On the other hand, VBNT proposes the concept of *'acceptance of new environmental paradigm'*, which is influenced by *'values'* (positively by *'biospheric'* and *'altruistic'* and negatively by *'egoistic'*) and influence *'awareness of consequences'*. VBNT keeps personal norms as the only driver of behavior, which is divided into three categories: *'environmental citizenship'*, *'policy support'* and *'private sphere behaviors'* [37]. On the other hand, theory of social learning (TSL) explains human behavior as a *"continuous reciprocal interaction between cognitive, behavioral and environmental determinants"* [38]. One of the most studied and determinant interactions

is the one among people, which is based on sharing ideas and experiences. TSL researchers show that self-experimentation (trial and error), peer learning, and collective learning are effective for energy-related behavior change [9,39]. Beside theoretical extensivity of TPB among psychological theories and models of energy-efficiency-related occupant behavior, VBNT is the one most prone to use for quantitative evaluation of behavioral influencers of energy use and energy policies.

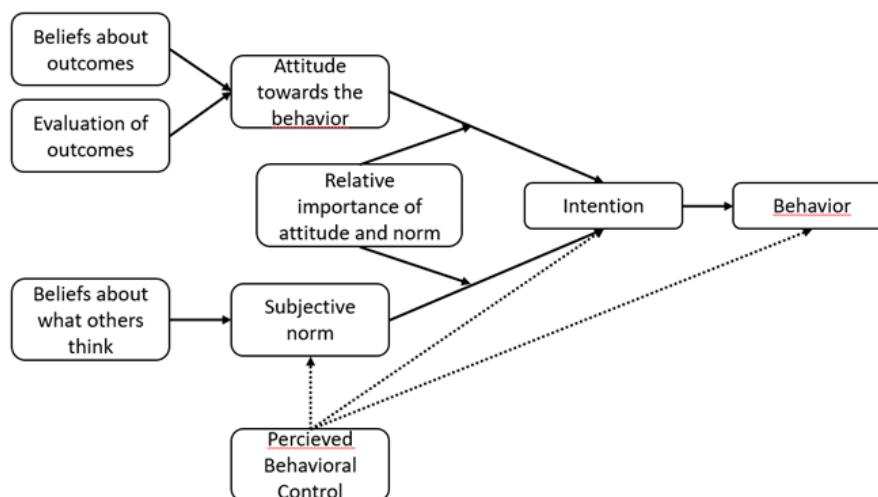


Figure 3. Theory of planned behavior (TPB) (Adopted form [9]). TPB is one of the theories that has high theoretical potential for application to building energy efficiency systems.

2.1.3. Sociological Approaches

According to sociological approaches to energy use, individuals are not autonomous decision makers but instead their decisions are driven by social and technological factors and interactions. ‘Normal practice’ conceptualization of this approach focuses on ‘*construction and transformation of collective convention*’, which makes it possible to investigate ‘*symbolic and cultural dimensions*’ of everyday life and sustainability [40]. These dimensions embedded in daily life facilitate everyday practices within a social context. Accordingly, social practice theory (SPT) focuses on the formation process of them [41]. Jensen contributes to SPT by coining the concept ‘*performativity*’ in order to discuss the integrative role of ‘*cultural, discursive, political and material arrangements*’ for the spatio-temporal configurations and consumption dynamics of practices [42]. Besides benefiting deep theoretical insights provided by SPT, it is also centered some practice-based real life studies. An important example is the Sustainable LivingLabs, which are to facilitate user acceptance and analyze routine behaviors by means of a practice oriented approach for sustainable product service system innovations [43].

From another point of view, actor-network theory (ANT) provides a framework for a large set of domains to understand dynamic interactions (both competitive and cooperative) among different actors (e.g., society, organization, agents and technological artefacts) [44,45]. Lutzenhiser notes that networks may construct barriers for energy efficiency innovations and organizational behavior change under the influence of factors like information, finance, design, industry culture, government, etc. [46]. In a similar manner, Anderson et al. proposes a model which is based on type and structure analysis of social networks in order to understand normative energy use behavior interventions [47]. On the other hand, lifestyle studies focused on impact of time use on activity patterns of people, which results in energy consumption. Lifestyle theory (LT) demonstrates the detailed analysis of behavioral patterns of energy consumption embedded in daily life [48]. SPT and LT provide effective conceptualizations to differentiate and transform the patterns and dynamics of energy use practices of everyday life.

2.1.4. Integrated Approaches

In addition to domain specific approaches reviewed above, several researchers have also developed integrated theories and models in order to get more coherent explanations (see Figure 2). As an example, Attitude-Behavior-Context (ABC) model states behavior as a function of dialect between personal attitudinal variables (internal factors like beliefs, norms and values) and contextual factors (external factors like legal factors, public policy or social norms) [9]. On the other hand, Triandis' theory of interpersonal behavior (TIB) includes '*habits*', '*facilitating conditions*' and '*affective factors*' into equation [9]. Triandis takes habits into the center of TIB and support it with '*intention*' to transform habits into behavior, whereas the transformation is under the influence of '*facilitating conditions*' [49]. Moreover intentions by people have three antecedents: '*attitudes*' (influenced by evaluation and beliefs regarding to outcomes), '*social factors*' (influenced by '*norms*', '*roles*' and '*self-concept*') and '*affective factors*' (influenced by '*emotions*') (Figure 4) [9].

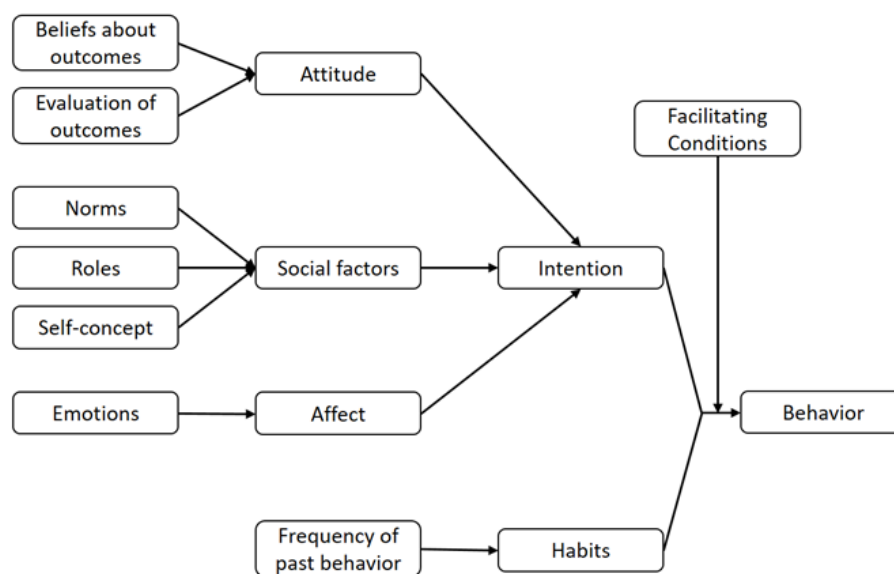


Figure 4. Triandis' theory of interpersonal behavior (TIB) (adopted from [9]). TIB highlights the crucial role of intentions and habits under the influence of facilitating conditions. When TIB is applied to building energy efficiency domain, innovative technologies can be considered as facilitating conditions.

Focusing on consumer lifestyles for environmental sustainability, the motivation-ability-opportunity (MAO) model of behavior studies states that behavior is determined by motivation (includes beliefs, attitude, intention and social norm), ability (includes habit and knowledge) and opportunity ('*objective preconditions for behavior*'), and in turn behavior influences beliefs and ability [50]. Based on cultural theory, lifestyle, and system thinking, "the energy cultures framework" (ECF) is also proposed for energy behavior [13]. ECF explains customer energy behavior in terms of interactions between cognitive norms (social aspirations, expected comfort levels, environmental concerns), material culture (insulation, heating devices, energy sources, etc.) and energy practices (number of rooms heated, heat settings, etc.) [13,51]. Being extendable with MOA and other theories, TIB provides deep insights and effective perspective to understand and transform energy efficiency-related occupant behavior, which is driven by both social and physical factors.

2.2. Overview of the Innovation Studies for Energy Efficiency in Building

Being subject to systematic investigation in terms of its economics, policy, and management for almost 100 years, research on technologic innovation turns out to be a scientific specialty for the last 30 years and generally referred as 'innovation studies' (IS) [52]. The way for this specialty is mostly paved by the comprehensive review articles by Freeman, Nelson and Winter, Dosi, Griliches and Brown,

and Eisenhardt during the last quarter of 20th century [53]. Moreover, one of the early and highly influential conceptualizations of the field, namely ‘*Diffusion of Innovations*’ is proposed by sociologist Rogers in 1962 [54]. Another model for new consumer products is formulated with the perspective of marketing research by Bass in 1969 [55]. These models for the diffusion of innovative products are applied to many different fields during following decades. They established the foundations of IS along with some other conceptualizations from economics, organizational studies, psychology, and political science [53]. During the 1980s and 1990s, new models, theories and frameworks were developed to explain the evaluation of innovation activities, organizational dynamics of innovation, and nationwide innovation systems [56]. Beside the mainstream research on technologic innovation, there are applied studies focused on meeting theoretical perspectives of mainstream research with human factor. Becoming prevalent in the 2000s, these are also applied to eco-innovations. Social practice theory (SPT) and the technology acceptance model (TAM) are two well-known examples of those and discussed in more detail in the following subsections.

Due to the complex nature of the design, construction and operation of buildings, there are both intrinsic (invention processes) and external (implementation of solutions) challenges for building energy efficiency innovations. Darko et al. provides 26 barriers of innovation in green building technologies (GBTs) according to the literature research and the expert surveys they conducted [57]. In their listing, the top five barriers (based on their statistical analysis) are: “*resistance to change from the use of traditional technologies*”, “*lack of knowledge and awareness of GBTs and their benefits*”, “*higher costs of GBTs*”, “*lack of green building expertise/skilled labor*” and “*lack of government incentives/supports for implementing GBTs*”. (Note that, the first one is a typical example of human behavior, which is relevant for any eco-friendly innovation and can be best understood with behavioral concepts, theories or models.) Noailly showed the impact of environmental policy instruments (energy standards, taxes and governmental budget for R&D) on energy efficient technology innovations for buildings (patent counts for insulation, boiler, lighting technologies) [58].

In addition to studies that aim to determine crucial barriers, drivers and acceptance of innovations for sustainable buildings, there are theoretical conceptualizations which focus on individual or society based dynamics of innovation. These studies are historically rooted in concepts of innovation diffusion, innovation adaption, social practice, technology acceptance (as discussed above), and further discussion including the eco-innovations perspective is provided in the following subsections. Figure 5 shows the tree of concepts, theories and models of innovation studies, which are related to building energy efficiency and Table 2 provides corresponding references in a classified manner.

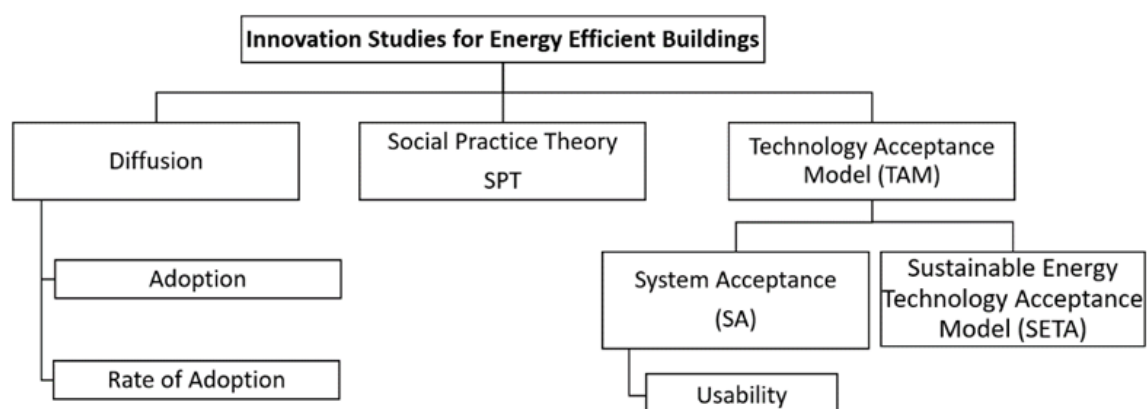


Figure 5. Concepts, models, and theories of innovation studies for energy efficiency in built environments. These topics are applied to variety of research fields and seen to be capable of providing insights and practical tools for building energy efficiency research.

Table 2. Summary of innovation literature for building energy efficiency.

Branch	Theory and Models	Important Concepts	References
Diffusion	DT	diffusion, adoption, rate of adoption, communication channels, social system	[12,54,55,59,60]
Social Practice	SPT	routinized practices, everyday life, transitions, patterns of meaning, competence, materials	[42,43,61–67]
Technology Acceptance	TAM	perceived usefulness, perceived ease of use, acceptance, usefulness, usability, technology attributes	[68–72]

2.2.1. Diffusion Theory

One of the important conceptualizations of the early innovation studies was innovation diffusion. According to Rogers' diffusion theory (DT), innovation diffusion is *"the process by which an innovation is communicated through certain channels over the time among the members of a social system"* [54]. Regarding to time content of this definition, Rogers states that *"rate of adaption"* for most of the innovations is in s-curve shape and the exact shape (steep or gradual s-curve) is characterized by the specific properties of other concepts included in the definition: innovation itself (practice, object, etc.), communication channels (informative or persuasive), and the social system (via social norms, opinion leaders, etc.) [54]. Rogers also classifies adapters of an innovation according to their timing to adopt an innovation (*"innovators"*, *"early adapters"*, *"early majority"*, *"late majority"* and *"laggards"*) [54].

Bass has also focused on timing of initial purchases of innovative products and formulated the entire diffusion process in two parts. The first part is defined as a continuous model and formulated as a density function of time to initial purchase. The second part is defined as a long-range forecasting problem and the formulation is assumed to be characterized by predictions of timing and magnitude of the sales peak of technology under consideration [55]. Accordingly, Bass categorized adapters in terms of timing as innovators (who behave individually) and imitators (influenced by other social actors) [55].

Innovation diffusion approach is mostly focused on formulating the speed of diffusion by time which is restricted to be determined by external (societal) factors which are disseminated by means of communication tools [59]. In the same manner, Karakaya et al. provides a comprehensive review on the contributions of economics, sociology, management, and marketing to understanding of diffusion of eco-innovations and also suggests discussing behavioral concerns and decision making process of consumers [12]. Additionally, Mlecnik shows the benefits of continuous learning, vision development, coherent communication and network formation for stimulating the adoption of innovation (in a passive house network). Their study effectively uses the concepts of behavior change and synergy [60]. Being applied to different research areas and large number of field studies, rate of adaption formulation offered by Rogers can help researchers and companies understand customer response to energy efficiency products and services.

2.2.2. Social Practice Theory

Another branch of research developed to understand the dynamics of energy efficiency innovations is focused on the social practice theory (SPT). Although it can be used for energy-efficiency-related behaviors of people, some versions of SPT are applied directly to innovation studies. As mentioned above, instead of focusing on individual-based factors, SPT deals with recreation/renovation of social practices in order to understand energy behaviors [61]. Similarly, when used in innovation studies, SPT is basically used to interpret the routinized practices as well as the embedded dynamics of innovations and the new ways of consumption into the daily life [42]. Accordingly, SPT experimentation deals with *"disruptions, challenges and changing conditions in everyday*

life” [62]. Moreover, SPT also deals with distributed nature of practices and the participation of individuals to sustainability transitions [62].

Having such a comprehensive point of view, researchers benefiting SPT have designed experiments focused on daily life for long time intervals (i.e., several years), including the experimentation for energy consumption in social housing [63,64]. Hansen discusses agentive relationship between smart grid technologies and energy practices of prosumers [65]. Based on its insightful approach, other researchers apply SPT directly to design of products, services and product-service systems for energy efficiency solutions [66]. According to SPT, social practices are outcomes of patterns of meaning (why?), competence (how?) and materials (what?) [67]. Better understanding of these embedded patterns highlights key points in a design process instead of focusing on specific aspect(s) of user behavior. Extending these ideas, Liedtke states that SPT and open innovation (user- and stakeholder-integrated) are the two effective tools of investigating every-day-practices (especially in ‘Sustainable LivingLabs’) and overcoming cultural barriers for sustainability transitions [43]. Sustainable LivingLabs seem to be the best idea to develop these interactive tools better and transform them for everyday use.

2.2.3. Technology Acceptance Model

In parallel to exponential increase of innovative products in information technologies sector during last decades, new concepts need to be developed to understand interaction of people with the new products and their interfaces. Since this interaction depends highly on human perceptions, Davis et al. reformulated TRA in a way that ‘perceived usefulness’ and ‘perceived ease of use’ lead to behavior intention which is the determinant of actual usage [68]. This is called the technology acceptance model (TAM). As the technologies become more dependent on computers and control over smart interfaces becomes more popular, its extensions are derived and adopted to large variety of sectors [69]. As the empirical studies increased, theoretical sub-branches of acceptance and new conceptualizations are developed for a better understanding of human interaction with digital interfaces. Nielsen’s definition of system acceptability is one of the most commons of those. It consists of two dimensions: practical acceptability and social acceptability where practical acceptability has sub-branches, including usefulness and usability, among others. All factors included in Nielsen’s model of system acceptability and their hierarchy is shown in Figure 6 [70].

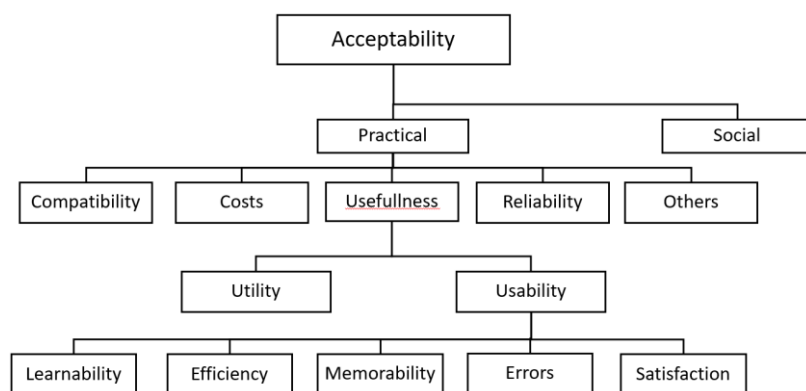


Figure 6. Nielsen’s model of system acceptability (adopted from [64]). In parallel to digitalization in energy efficiency domain, Nielsen’s model appeared to be an effective tool to understand human interaction with digital energy efficiency solutions.

As touchscreen and smartphone applications are increasingly used for controlling building systems, their acceptance and usability turn out to be important factors for achieving energy efficiency. In this context, smart meters, smart thermostats, and building monitoring systems are typical technologies to conduct research for their impact on energy efficiency as well as user acceptance and usability. An extended version of TAM is also outlined, which additionally includes economic benefit,

social contribution, environmental responsibility and innovativeness in order to study acceptance of a home energy management system [71]. This study by Park et al. shows that intention to use is mostly influenced by usefulness (more than ease of use), which is mainly driven by economic benefit, environmental responsibility and innovativeness. Similarly, sustainable energy technology acceptance (SETA) model was proposed, which consist of individual differences (trust to utility company, politic orientation, etc.) and technology attributes (usefulness, cost, privacy) and demographics (gender, income, etc.) as determinants of adoption intention [72]. Interestingly, the field study for SETA model shows that smart meters are perceived as a tool for sustainable energy rather than a facilitator of energy efficiency. TAM and its extended versions are highly capable of explaining user interaction with innovative products and services and also evaluating market response to them.

The present study provides an overview the fundamental content and concepts of B&I studies separately before assessing and discussing the interdisciplinary dialog between them. This work is not intended to analyze and compare the details of B&I models and theories in the field of building energy efficiency. The above discussion is based on manual review of related papers, which is limited in number to get an overall understanding their interrelationship. Thus, we support this review with a network analysis of leading concepts in the following section. This comprehensive approach is expected to help understanding of transdisciplinary research needs for complex engineering and social aspects of building energy efficiency problem, and its potential impact on the sustainability.

3. Network Analysis of Key Concepts and Visualization of Interdisciplinary Dialog

B&I studies span an extensive scientific landscape, as they are limited to building energy efficiency domain. Thus, it will be useful to provide an analysis of key concepts based on Clarivate Analytics Web of Science (WoS) bibliographic database, as such a study and analysis give an overview of interdisciplinary dialog and foundations of relationship among these fields [73]. In order to determine the key concepts facilitating interdisciplinary dialog between B&I studies, we conducted a network analysis of vocabulary embedded in our original database.

3.1. Method for Network Analysis

The process of network analysis starts with creation of original dataset on WoS platform that provides necessary metadata to conduct the analysis. A set of keywords is configured for the *TITLE* and *TOPIC* options of the platform by reviewing the influential research and review articles selected among the ones discussed in the Sections 1 and 2. Provided categories by the platform is also filtered by their relevance to content of this paper. Appendix A provides a full list of entered keywords and selected categories. After the manually elimination of irrelevant and identical entries, there were 737 unique papers in our original dataset. Here it is important to note that such a way of building a dataset may not have included all the relevant papers of the subject under investigation. The selected keyword and categories as well as the searching and indexing mechanism of the platform introduce a bias for the outcome. Being aware of this limitation, we intended to get most comprehensive dataset to represent the purpose of the analysis. So, it would be better for the reader to focus on general structure of relations and interdependence of concepts instead of exact value of specific measures.

The next step for the analysis was the determination of the most frequent terms in the 'Abstract', 'Title', 'Original keywords' and 'New ISI keywords' columns of the original dataset and the interaction between them. For this, we used the word co-occurrence analyzer of Sci2 software which provides a network where the words are represented with nodes and the strength of the interaction (co-occurrence) among them is represented with edge weight [74]. After the elimination of less frequent (<3 times), loosely relevant and too general terms, we get a network composed of 38 nodes and 179 edges. These nodes are then assigned categories (behavior, innovation or common) by referring to research and review articles used in first step (keyword selection). Since the WoS database doesn't have a default attribute for such a clustering, the assignment process is performed manually (see Appendix A for details). It is important to note that the process followed at this step brings together the subjectivity

of categorization. So, like in the first step, the reader should concentrate on the general structure of the categorization instead of assignment of specific terms.

The last step for the analysis was the creation of visualizations. Using the embedded tools of Gephi software, node size attribute is set to betweenness centrality and label size attribute is set to total reference to each term in original database. Appendix A provides the details of the each step of the analysis process, which makes it possible to replicate the analysis. We also provided the original dataset file in supplementary materials.

3.2. The Analysis

The earliest paper included in the original dataset was published in 1991 and it includes papers up to the first quarter of 2018. Timely distribution of the number of papers published in each year and the total number of citations of these papers are shown in Figure 7. It can be observed from Figure 7 that the total number of publications included in our original dataset is very few up to the year 2005 but some of them are well-cited. These would be the well-known reviews of the B&I literature. Moreover, there is a continuous increase in number of publications after 2005 whereas the number of citations continuously increases up to 2011 and then fluctuates. The increasing trend of yearly number of papers and the considerable amount of citations to those publications show the increasing interest to B&I studies, especially after 2005. Such a trend inevitably brings together an increasing interdisciplinary dialog among these research fields and the need for studies that use hybrid conceptualizations.

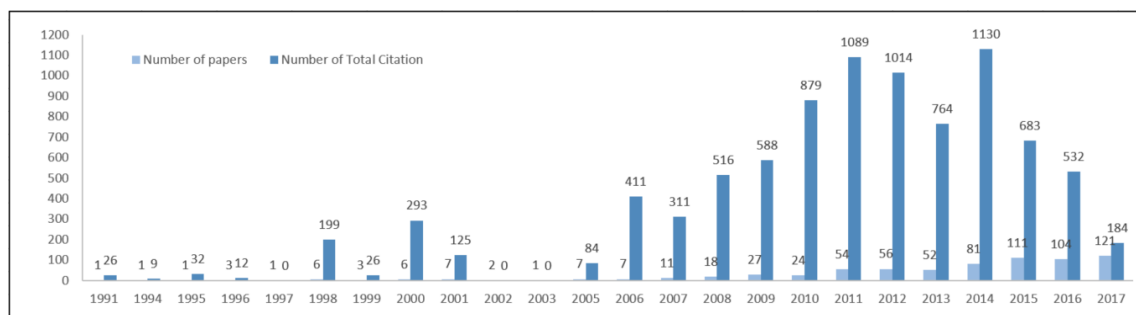


Figure 7. Yearly distribution of number of papers included in original dataset and the total number of citation for these publications. The increasing trend of yearly number of B&I-related papers and the considerable amount of citations to these publications facilitate the conditions for a better interdisciplinary dialog.

The visual outcome of the network analysis explained in Section 3.1 is shown in Figure 8, which constitutes 3 categories with different colors: behavior-related terms (blue cluster), innovation-related terms (green cluster) and common terms (cyan cluster). Note that these clusters are not dominated by the keyword configuration entered to WoS to create original dataset. There are many terms (nodes) in the network that were not included in WoS search keyword list (given in Appendix A). Thus, the network representation is useful to observe the (i) top relevant terms (nodes), (ii) total reference to each term in original dataset (label size), (iii) betweenness centrality of each term (node size), (iv) the frequency of co-occurrence of them (thickness of edges), and (v) the interaction of groups (linkage patterns). These points are further discussed in following paragraphs.

It can be observed in Figure 8 that behavior studies dominate the research landscape with 27 terms whereas there are 6 terms belonging to innovation studies and 5 terms in commons. In terms of their occurrence in the original database (reference score), top five terms of the network are behavior (85), barriers (28), determinants (20), models (19) and adaption (18). Note that, the list includes terms from each cluster. Moreover, the behavior cluster is dominated by the terms related to behavior theories and models (e.g., habits, attitudes, social practice, norms, etc.). In parallel to the domain review in Section 2, we can conclude that determinants offered by TRA, TIB, ABC, and SPT are well represented

in the network (frequently occurred in original database). For example, according to TRA, behavior is driven by ‘behavioral intention’, which has the determinants ‘attitude towards behavior’ and ‘subjective norms’. The terms ‘attitude’ and ‘norms’ in the network refers determinants of TRA, which indicates the acceptance of these determinants by literature.

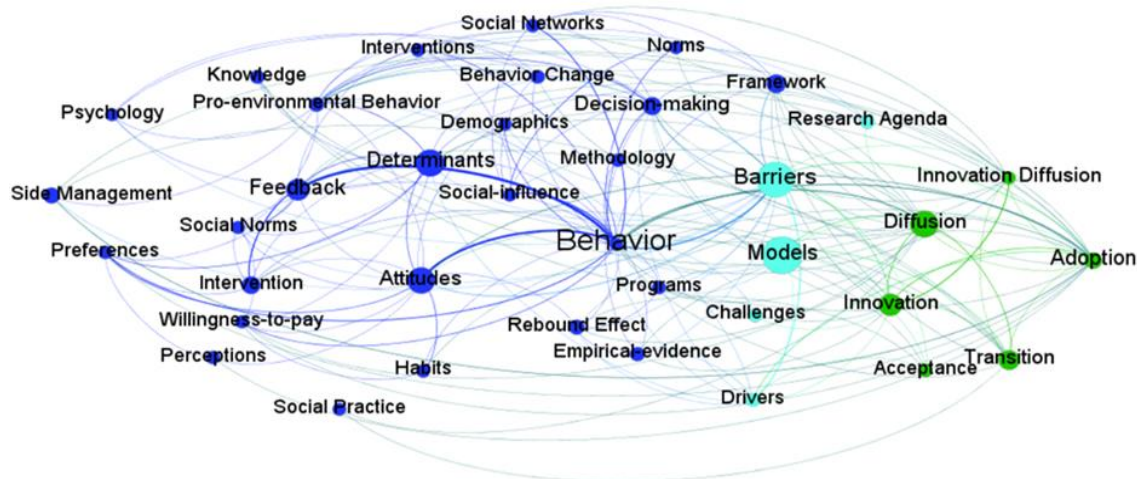


Figure 8. Key concepts of behavior and innovation research in the field of building energy efficiency. Here, the blue nodes represent behavior-related terms, green nodes represent innovation-related terms and the cyan nodes represent common terms of both sets of literature. The figure shows that behavior studies dominate the conceptual landscape in the original dataset. Also, the interaction between B&I clusters seem to be weak since edges with different colors rarely mesh with each other. This is an indicator of the fact that interdisciplinary dialog between B&I studies has not matured as of yet.

Here it is important to note that we don't claim the superiority of TRA (or any other) approach to any other one; but instead we show the frequency of its content to be discussed in the literature. As an example, TPB includes these determinants but also the ‘evaluative beliefs’, ‘normative beliefs’, ‘motivation to comply’ and ‘perceived behavioral control’ but none of these additional terms are represented among the terms in network. Obviously, this would be related to limitations of this study or the late penetration of TPB (when compared to TRA) to literature. However, none of these reasons make TPB less important or successful.

Being subject to this notification and following a similar evaluation for other theories reviewed in Section 2, we conclude that TRA, TIB, ABC and SPT contain the determinants well discussed in the literature. Note that TIB and ABC are integrated approaches and SPT is applied to both B&I studies (see Section 2), which shows the relevance and importance of interdisciplinary approaches. On the other hand, note the presence of just a few but highly frequent concepts of innovation literature (e.g., diffusion, adoption, acceptance and transition). These are together with behavior-related concepts and with a similar frequency (labeled in similar sizes). This indicates presence of the attention paid to innovation studies and also refers to its limited interaction with behavior studies in the field of building energy efficiency.

One of the important concepts of the network analysis is the metric called ‘betweenness centrality’ (BC), which represents the importance of a node to bridge different clusters in a given network [75]. So, it can provide a better understanding of interaction between clusters in a given network. Node size in Figure 8 is scaled in accordance with BC score of each node. Accordingly, the terms in commons cluster are expected to have highest centrality by their definition (e.g., *models* = 1380, *barriers* = 1296). Thus, excluding them, top five terms with the highest BC score are *determinants* (810), *diffusion* (768), *attitudes* (758), *innovation* (520) and *feedback* (514). These are the leading terms that establishes interdisciplinary dialog between B&I studies related to energy efficiency research in built environments. The terms *determinants*, *attitudes*, and *feedback* are the most frequent members of behavior clusters used

by innovation studies. Similarly, two other terms with respectively high BC scores in innovation cluster, namely *diffusion* and *transition*, are frequently used by behavior studies. These two examples show that key concepts of innovation studies ‘diffuse’ to behavior literature, and vice versa. Accordingly, the green edges demonstrate penetrative pattern to ‘blue zone’ of the network given in Figure 8.

However, interaction among behavior and innovation clusters does not seem to be strong. This can be observed with the lower frequency of co-occurrence (represented with edge thickness in Figure 8) of terms belong to different clusters. Top four most frequent co-occurrence is between behavior-related terms (*feedback-behavior*, *attitudes-behavior*, *feedback-intervention*, *social influence-behavior*), following two is touching to common terms (*behavior-barriers*, *barriers-drivers*) and yet the seventh is between B&I-related terms (*behavior-adaption*). Lower rank and rate of frequency of co-occurrence of B&I-related terms shows the lack of strong interactions among B&I studies. Accordingly, the linkage (edge pattern) of the terms belong to B&I studies is seen to be weak.

3.3. A Leaner View of Interdisciplinary Dialog

Both B&I-related concepts are well-studied topics in building energy efficiency domain, consequently the visualization given in Figure 8 demonstrates intense internal relationship between their own concepts. Since the main purpose of this paper is to provide a better understanding of this interdisciplinary dialog, we developed a bipartite graph as a supplementary visualization to network analysis. For this, we eliminated internal links of each cluster manually from the dataset of network graph and created a relatively simpler representation (see Figure 9). Here, we also eliminated the terms belong to commons cluster for convenience since their connectivity is obvious. The links in the bipartite graph don’t have the weight attribute but instead they simply mean that two corresponding terms co-occurred at least three times in the original dataset. From this point of view, the terms with highest mating score (total number of items matched from opposite cluster) from the behavior cluster are: *behavior*, *decision-making*, *pro-environmental behavior*, *rebound affect*, and *framework*. The term ‘*behavior*’ mates with all the terms in the opposite cluster whereas decision making has only one absent link which is the one with the term ‘*transition*’. The other three terms (*pro-environmental behavior*, *rebound affect* and *framework*) have three common mating: *adaption*, *diffusion* and *innovation*.

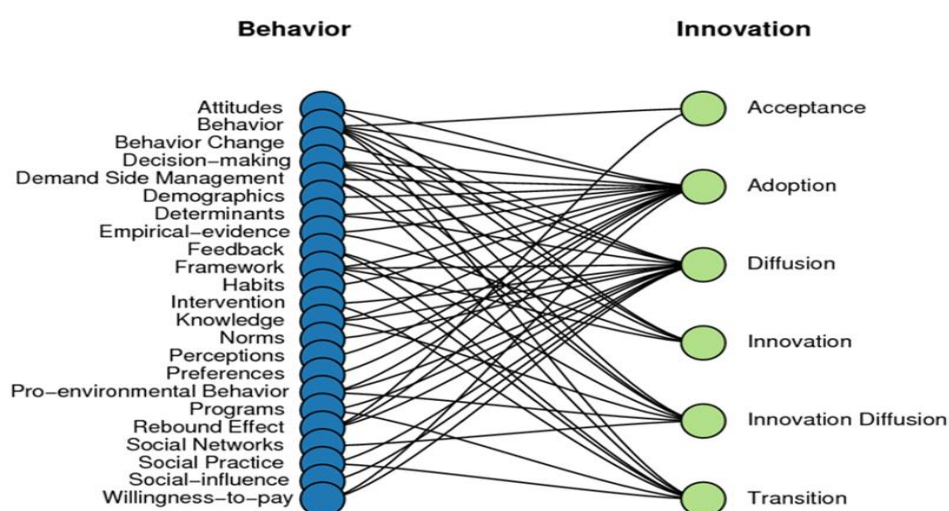


Figure 9. Bipartite graph for the leaner representation of the relationship between behavior and innovation clusters. The most important terms which facilitate the interaction among B&I clusters are ‘adaption’, ‘diffusion’, and ‘decision making’. This shows that the behavior studies use the important concepts of innovation studies more effectively than in the opposite case.

The terms in the innovation literature with the highest mating score are: *innovation*, *adoption*, *diffusion*, *innovation diffusion* and *transition*. Unlike the term ‘*behavior*’, the term ‘*innovation*’ mates with

few percentage of the terms in the opposite cluster, namely: *framework*, *empirical evidence*, *attitudes*, *behavior* and *decision making*. Terms '*adoption*' and '*diffusion*' mates with high percentage of the items in the behavior cluster whereas the others have lower percentage. Such an interaction patterns suggest that, beside the fundamental terms '*behavior*' and '*innovation*', the most important terms that facilitate the interaction among B&I studies are '*adaption*', '*diffusion*' and '*decision making*'. This is in accordance with the interpretations of Figure 8.

Based on this observation, we can say that behavior studies use the important conceptualizations of innovation literature more effectively whereas the innovation studies don't take advantage of concepts, models and theories of behavior studies thoroughly. This indicates the limited utilization of the conceptual potential of behavior literature by innovation studies, which results in confinement of human factor in innovation studies to purchasing decisions. In other words, innovation studies would benefit non-economic behavior conceptualizations to overcome this restricted utilization of its potential and further possibilities in this manner are discussed in detail in Section 4.1.

Besides the restricted utilizations of conceptual and methodological interaction between B&I studies, certainly there are considerable common attitudes that can be observed via Figures 8 and 9. BC (node size) and co-occurrence frequency (edge thickness) attributes of Figure 8 and mating score (number of connection with the other cluster) attribute of Figure 9 provide deeper insight regarding to common points. One of the most obvious of them is reflected with the high scores of terms '*adaption*' and '*diffusion*' in terms of attributes mentioned above. This shows the acceptance of the terms by both sets of literature, which simply refers to the need for defining and quantifying the approval (or rejection) of a proposed behavior or innovation by society. However, their attitude differentiates in terms of observation parameters. Behavior studies try to follow the change in personal or societal determinants (e.g., attitudes, perceptions, norms) whereas the innovation studies mostly focused on market response and consumption patterns (see Section 2). Thus, these terms are valuable examples to show the differentiation of attitudes of B&I studies for common points.

It can be claimed that a specific term assigned to a cluster in Figure 8 or in Figure 9 belongs to another cluster, so our comments regarding to its interaction with others may mislead. We would like to remind that the methodology we followed (Section 3.1 and Appendix A) is not purely objective; instead, it has subjective characteristic especially while conducting manual assignments. Thus, we don't claim to have golden rules of assessing interaction between B&I studies objectively for building energy efficiency research but we intend to develop arguments supported with objective metrics as much as possible. Instead of focusing on specific nodes or edges, we suggest to look at the general structure of the network in accordance with the purposes and capabilities of this kind of network analysis.

4. Discussion

In parallel to the significant accumulation of scientific knowledge during the last century, the differentiation, specialization and fragmentation of science into disciplines was a major trend in scientific research [76]. As in many other disciplines, B&I literature has also been developed based on its distinct research approaches for different applications. Even if they can be limited to sub-focus of energy use in built environments, still both areas show a variety of approaches and methods to deal with some common problems [77]. As the reviews in Section 2 and the analysis in Section 3 indicate, there is a shortage of interdisciplinary dialog between B&I studies. A transdisciplinary approach to understand energy use in built environments can facilitate and benefit from interaction between B&I studies [78]. However, facilitating such a dialog would lead to unforeseen methodological challenges. The only way to establish links between the proposed innovative energy efficiency interventions and societal impact is to leverage an interdisciplinary dialog [79]. Such a dialog would allow us to push boundaries of research for energy efficiency in built environments. Thus, in this section of the paper, we highlight the potential contributions of B&I studies to each other. Lists of these contributions are given in Figure 10.

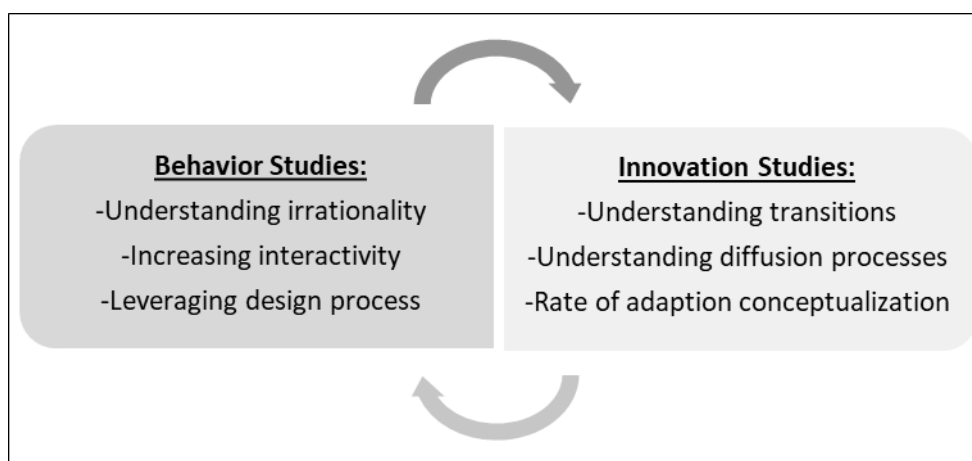


Figure 10. Contributions of innovation and behavior studies to each other. These two realms should not be studied alone; they should be discussed with collaborative approaches to develop effective strategies.

4.1. Influences of Behavior Studies to Innovation Studies

Any innovation is subject to a series of behavioral responses by its users. For the mainstream innovation research, humans are just considered as being ‘customers’, a term used loosely here. Most of the time, the consideration of human behavior is limited to economical behavior. However, better understanding of behavioral concepts (i.e., norms, practices, values, among others) can help experts to develop behavior aware energy efficiency products, services and policies facing with less resistance by the users. Having high potential to contribute several aspects of environmental problems, behavioral concerns are between the key concepts of sustainable and low capital-intensive solutions where solely technological or economical innovations are insufficient [80]. In this section, we discuss three potential contributions of behavior studies to innovation studies for: (i) better understanding of irrationality, (ii) increasing human–system interactivity, and (iii) leveraging design process of products and services. They are discussed below.

Behavioral concerns can help researchers, technology developers, and policy makers to harness the benefits of understanding the irrationality embedded in everyday life. Rebound effect is one of the topics where the behavioral economics has been contributed and promises potential for more savings [81]. Beside economic evaluations, irrationality in human decision making has more dimensions like variety in preferences, inconsistency in time use, behavioral inertia, endowment effect and reciprocity [82]. Furthermore, as Jaffe discussed, a deeper relationship between users’ perception of ‘optimal’ energy usage (which can be explained with psychological approaches, see Section 2.1) and adaption rate of specific energy saving technologies can be established [83]. The personal and social factors that influence adaption of investment measures to improve energy efficiency in buildings is also emphasized [84]. Impact of economical, sociological and neighbor dimensions (e.g., education level) of adaption decisions for energy efficient HVAC systems both for new constructions and renovation projects was shown to be important [85]. Thus, behavioral research (both economic and non-economic) has a latent potential to extend its capacity by paying more attention to understand irrationality for the adoption of long-lasting investments for energy efficiency innovations, as mentioned by Stern [86].

Recent developments in smart systems make it possible to create more efficient energy systems for built environments with higher adaptability to its surrounding and higher interactivity with occupants. These developments support the users with higher connectivity and customized experiences [87] as well as simplified declaration of preferences to the systems by means of interactive interfaces. On the other hand, information transferred to users by means of these interfaces can influence the user behavior. Various feedback-driven behavior change mechanisms have been studied in the literature and tried in the market based on different behavioral concerns [88]. Smart thermostats and smart electricity meters are the two of the most emphasized topics of studying and developing feedback

mechanisms and interaction backed with behavior modeling and behavior theories and models [89,90]. For example, Ramos et al. showed that behavioral concerns can be considered as a design influencer of energy efficient system innovations since the type and amount of information provided to occupants by means of feedback mechanisms also effect the system design [91]. Once the engagement of users with these kind of systems is realized, the interaction of users with each other by means of various platforms (specific mobile apps or social media) can also leverage user persuasion and innovativeness of the proposed systems [92].

Beside understanding irrationality and increasing interactivity, it is also possible to take advantage of behavioral concerns directly in product or service design, development and management. To facilitate this integration for design phase, one can use design thinking and human-centered design approaches, keeping in mind the behavioral concerns [87]. Some examples of innovative technology applications that are proven in literature to be enhanced by means of such an interdisciplinary methodology are (i) gamification and mobile games [93], (ii) smart power strips [87], (iii) sensor applications [94], (iv) building automation and energy management systems [94], (v) personalized comfort systems [95], and (vi) building energy modeling and simulations [96]. As the last example implies, beside building systems and services, behavior modeling can directly contribute to innovations in design of buildings themselves by leveraging the perception of dynamic interactions in built environment [97]. In addition to design processes, economical and psychological behavioral concerns may also help to understand failures of energy efficiency products and services in innovation markets, which is crucial for product management [98].

4.2. Influences of Innovation studies to Behavior Research

Most of the products and services in building energy efficiency domain are innovative by their nature. The penetration of any innovations intends to bring change into daily life of end-users. Especially the technological innovations supported with behavioral considerations are expected to change long-time governing practices of daily life (even if the dialectic relationship among technology and human behavior is not well-understood) [99]. Not surprisingly, they face resistance for change, which is valid for other domains (transportation, health, crime, etc.) as well. Thus, beside their domain-specific challenges, behavioral energy efficiency interventions are also subject to common resistance for change [100]. Being intended to change daily habits and practices, behavior studies may benefit from innovation studies for a better understanding of human response (acceptance or refuse of change) to behavior based energy efficiency interventions.

Innovation studies involve the term ‘transition’. It is developed to deal with the process of “*problem and dynamics of how to transform existing socio-technical systems to more sustainable configurations*” [101]. Transitions research on sustainability innovations highlights the variety of participants involved in the process (society, policy, companies, etc.) and considers the synergy among them as an important driving factor [102]. Intermediary actors attach importance to facilitate this synergy for all kind of innovation transitions as well as building energy efficiency [101,103]. Kuckshinrichs evaluates the social impacts of energy efficient technology transition by means of building refurbishment programs supported by governments (as an intermediary actor) [104]. Beside a macro-scale evaluation of impacts of eco-innovations, transition conceptualization is also applied directly to behavior change progress in order to figure out relevant interventions of individual energy savings [12,105]. In parallel to recent technological advancements, big data and social network innovations are considered to be facilitator for the monitoring of ‘behavior transitions’ of individuals [106]. Thus, one can take advantage of transition concept of innovation studies for a deeper understanding and management of resistance to change faced by behavior-based interventions for building energy efficiency.

Some behavioral scientists have already focused on the economic decision-making process of individuals in order to understand their preferences regarding to energy efficient products or services [107]. Initially RCT and UT (economic benefit oriented) and then behavioral economical approaches (including psychological and sociological concerns) provided some insights regarding the

user preferences and archetypes (Section 2.1) [22]. Some intervention tools like smart submetering and energy efficiency labels (e.g., Energy Star) have been developed for the marketing of those by taking advantage of behavioral economics [81,108]. However, a better understanding of market penetration and dissemination of innovative products and services requires more specific considerations. Conceptualization of ‘diffusion of innovative technologies’ and related theories of innovation literature deal with the role of social communication and the stages of market evaluation. As an example, based on real market data, Schleich empirically shows the relationship between diffusion of energy efficiency technologies and behavioral concerns such as the role of information about energy consumption patterns [109]. Moreover, diffusion concept is also shown to be applicable to behavior studies (behavior diffusion) to discuss the agentive relationship among technological innovations and energy consumption behavior [110]. So, for behavior researchers, it is possible to get more comprehensive understanding of response of society to behavior oriented energy efficiency solutions by taking advantage of diffusion concept of innovation literature.

Beside transition and diffusion concepts, “rate of adaption” of innovation studies may also help behavioral scientist to choose proper approach for specific cases. Rogers characterized the rate of adaption of innovations as an s-curve shape and classifies adapters of innovations in five groups: innovators, early adapters, early majority, late majority and laggards (see Section 2.2). Besides the rate of adaption, behavioral determinants for each of these groups are expected to be different. As an example, in terms of TSL researchers, innovators are more prone to self-experimentation whereas late majority and laggards are expected to be collective learners since there is a mature community at that stage of adaption and people tend to imitate successful interventions [39]. Similarly, TPB states the “beliefs about what others think” as an antecedent of a subjective norm that is expected to have higher weight for late majority compared to innovators or early adapters. Thus, benefiting rate of adaption concept of innovation studies can help behavior researchers to evaluate the relevance and the potential performance of candidate methodologies in a continuous way.

5. Potential Benefits of Interdisciplinary Dialog for Smart Thermostats

Thermostat is a good example for energy efficiency focused technologies, which is also subject to meet conditions for human dimension. One of the vanguards of heating, ventilation and air conditioning (HVAC) systems, Thomas Tredgold stated the multidimensionality of the design of these systems in the early decades of 19th century. In his book called ‘The Principles of Warming and Ventilating Public Buildings’, he provided a primary means of heat engineering for indoor environment under the topics of steam and heat distribution, fuel consumption, heat losses, ventilation, and boilers [111]. He also made stress on meeting these topics with human factor: *‘It is important to study the art of heat in order to find a combination between an equal degree of safety, cleanliness, and comfort, along with more healthiness and economy of a space’* [112]. Being clearly stated almost 200 years ago, multidimensionality of thermal management of indoor environment is still an active research area and today one of the most important mainstays of the topic is the thermostat.

Having a long historical background and large number of installations all around the world, current state-of-the-art thermostats are subject to discussions involving both the technology and human dimensions of the ‘art of heat’. The literature shows variety of ranges for potential energy savings with the effective use of them, which can vary in the range of 10–25% [113–115]. Besides, thermostats are also studied within the context of thermal comfort, indoor air quality, and behavioral economics [116,117]. Moreover, the cutting-edge concepts, like gamification and artificial intelligence, are also under investigation to make thermostats smarter and easy to use. Yet, thermostats provide a good opportunity to discuss and observe benefits of co-evaluation of B&I-related concerns. In this section, we briefly review the interest of B&I studies to thermostats and then discuss the pathways and benefits of interdisciplinary dialog to quantify their intangible and tangible contributions.

5.1. Perspectives of Behavior and Innovation Studies for Thermostats

Beside climate and physical characteristics of buildings, the difference between potential and actual energy savings of energy efficiency products and services is highly influenced by the occupant behavior [118]. In accordance with this fact, thermostat-related behavior studies of last decades mostly focus on modeling the use patterns of occupants and determining the correlation of this with the energy consumption [119,120]. Based on the technical architecture of the thermostat, on/off timing, temperature set-point preferences, differentiation of day-time/night-time set values, variations in seasonal preferences, occupancy profile and preferences for programming options are important topics under investigation for modeling occupant behavior [121]. Since the parameters related to these topics directly influence the energy consumption of buildings, behavioral interventions that can change them properly are expected to result in energy savings. Most common interventions in the literature for triggering behavior change are goal-setting and providing occupants custom information and feedback about their energy consumption and potential savings [110,122].

In contrast to high number of papers studying the behavior modeling efforts and designing interventions based on them, there are just few studies discussing behavior theories and models and their conceptualizations for a better understanding of thermostat usage practices, which shows how little the interaction is realized. Among a few researchers worked on the subject, Santin focused on linking the heating-related behaviors of occupants to energy usage profiles basing on the concepts like values, motivations, needs and attitudes (calling them '*cognitive variables*') which are fundamental concepts of behavior theories and models [123]. Supporting the proposed theoretical framework with a field experiment and a comprehensive statistical analysis, among some other interesting findings, she shows that even the occupants have considerable energy awareness, they may have higher consumption due to thermal comfort expectations. Gram-Hanssen provides a comprehensive theoretical analysis and empirical evidence of how can practice theory be used to understand the interdependency between thermal comfort and heating system usage patterns [124]. She analyzed the role of technologies, cultural myths, habits, knowledge and meanings to understand the collective and individualistic dynamics of thermostat usage. Raaij et al. offers a comprehensive behavior model, which involves most of the determinants mentioned in Section 2.1, and conclude with the (i) effectiveness of direct policy actions (like behavior advice) when compared to providing general information and (ii) importance of feedback for heating behavior change [125].

Thermostat-related innovation studies mostly discuss the usability of heating controls. The main reason for this would be the fact that for many people programmable thermostats are difficult to understand and occupants do not have confidence in, or lose motivation to effectively use, their available functions [121]. To circumvent this problem, Karjalainen modified ISO 9241–11 (1998) product usability framework for the development of office temperature control interfaces and compared the usability of several designs [126]. Some of the key findings of the study are related to the importance of (i) keeping occupants in the loop, (ii) using the same units for controlling heating and cooling, (iii) preferring simplicity for interface, and (iv) providing relevant feedback. An extensive report prepared by Department of Energy and Climate Change of United Kingdom follows the similar usability metrics and lays emphasis on (i) complexity of schedule setup, (ii) lack of error prevention, and (iii) lack of confirmatory feedback, among other design issues (iconography, visual design, etc.) for the existing products [127]. This means that new rules need to be developed and entered into the standards. Beside their usability, other factors included in TAM which are important to understand the adoption, misuse and better design of thermostats are: (i) the cost of the device, (ii) its compatibility with existing infrastructure of the building and (iii) utility incentives [121]. Note that these three concepts show the importance of B&I studies for the development of energy efficiency gadgets, and each of these concepts need to be discussed further for practical cases.

5.2. Thermostats as an Example of Interdisciplinary Dialog between Behavior and Innovation Studies

In this section, we discuss how an interdisciplinary dialog between B&I studies can help to improve design, acceptance, and operation of thermostats. It should be understood that we consider thermostats as an example, and similar analysis can be performed for other energy efficiency gadgets or interventions as well. Here, we attempt to propose three potential ways of improvement for future thermostat design strategies.

First, the behavioral concerns (like subjective norms, evaluative beliefs, habits, cultural factors) can help to construct a better understanding of irrationalities in adoption of new thermostats (see Section 4.1). In contrast to well-known benefits, their adoption is slower than expected for many parts of the world and most of adopters do not use important functions correctly [128]. This would be due to challenges in changing attitudes and subjective norms, which can be understood better with behavior theories. According to TPB (see Figure 3), one of the factors determining attitudes is evaluation of outcomes and that of subjective norm is perceived behavioral control. Thus, in order to leverage adoption of thermostats, researchers or companies can provide interactive tools (a sort of calculator) on their websites to help candidate customers to calculate potential savings. Such a tool showing the details of calculations with simple and clear instructions can provide transparency and increase the personal trust to a gadget. Similarly, a virtual model of the product available on a website which is controlling a virtual house can make it possible for customers to experience the product before purchasing. Such an experience may lead an increase in perceived behavioral control, which results in a positive change of subjective norms. Thus, the calculation of potential benefits and experiencing the usage of product may leverage not only the intention for purchase but also the effective use of thermostats. These and similar experiences eliminate or decrease the number of unclear aspects of a gadget for customers and minimize both the economic and psychological irrationalities while making decisions. Furthermore, once the customer visits the products webpage for such an experience, they may provide direct feedback that can provide hints for irrationalities. Simply put, as the irrationalities in innovation adoption are understood better by means of behavior theories and models, a better design of products, services and interventions would be possible which can accelerate the adoption of a product.

Second, the acceptance and usability of a gadget, the two important and interrelated concepts of innovation studies, can be leveraged with a behavior-driven design of augmented interactivity of thermostats and HVAC systems. Current literature considers thermostats as a digital interface and take advantage of tools and concepts originally developed for web based tools and mobile platforms. However, thermostats control the physical processes for human in living spaces. Their acceptance and usability should be discussed beyond just being an interface. As an example, a learning algorithm embedded in the software of thermostat can estimate the time interval of reaching a new set point (what time the room will be in desired temperature) and can augment the interaction of occupants with physical environment by means of this information. Furthermore, icons on thermostat or messages via smartphone applications that dissuade occupants from rapid temperature changes (which requires more energy) can help to save energy by changing attitudes and supporting motivations. Such an interaction scheme is consistent with TRA: it helps occupants to develop better '*attitudes*' for behavior change and to gain eco-friendly '*habits*'. In this case, thermostat itself turns to be a tool of '*facilitating conditions*' (see Figure 4). Thus, we can say that, behavior concepts can benefit to augment the interactivity of occupants with physical environments by means of digital technologies and this will leverage acceptability and usability of products for the sake of energy efficiency.

Third, the rate of adoption concept of innovation studies can be used for monitoring and changing the behaviors of a group of thermostat users in a dynamic way. A thermostat can share the information related to the preferences of other users in a close surrounding and can facilitate the formation of a user group via a smart phone application. This will help to develop '*social norm*' which is an important determinant of '*motivation*' in MAO model of behavior (see Section 2.1). For the '*innovators*' and '*early adapters*', the content of the feedback messages for motivation would be focused on formation

of the group and common targets whereas those may change for ‘late majority’ and ‘laggards’ as to be more competitive between individuals or groups. In other words, following the Roger’s s-curve model for the rate of adoption, a thermostat producer can develop custom messages for the better motivation of its user community, in parallel to diffusion stages of the products. Thus, innovation studies can add time content to the evaluation of behaviors and the design of behavior change interventions.

5.3. STC Applied to Thermostats

As the few examples provided above show, discussing B&I-related concerns of thermostats in tandem can facilitate the interaction between human and technology dimensions of thermostats. The STC conceptualization explained in Section 1 can be helpful here to get a wider perspectives. Once the target elements of ‘Human Factor’ and ‘Building Systems’ are determined, the problem metamorphoses itself into a hybridization of B&I concepts, models or theories, which interweave these elements. Figure 11 shows an example of the case-study application: thermostat-related concepts of human factor (awareness, feedback, habit, etc.) are deeply discussed by behavior studies and provides insight to innovation studies. Similarly, related concepts of innovation studies (e.g., interface design, scheduling) are well explained by innovation studies and can contribute to behavior studies. Such an enriched and interdisciplinary approach provides better understanding of human-building interaction. Thus, based on such a circular and continuous process based on structured interaction of B&I studies, the conceptual framework can make it possible to overcome the barriers for the diffusion of both better behaviors and new technologies. For the quantification of the process, one can take advantage of multicriteria optimization literature to find the most appropriate method for the intended problem and available data. In this sense, a good example of using multicriteria decision tools to investigate energy efficiency performance of digital energy services by evaluating behavior, innovation, technical and business dimension of energy sector was given by Goldbach et al. [129].

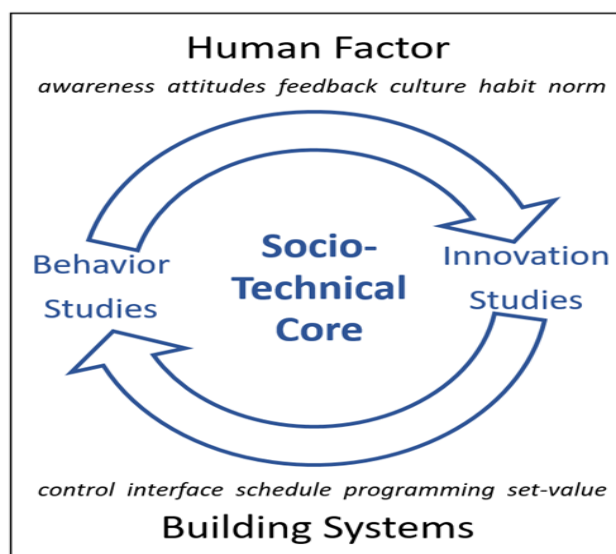


Figure 11. Sociotechnical core (STC) approach applied to smart thermostats: Behavior studies can facilitate the translation of the concepts of human dimension to innovation studies whereas the innovation studies can promote the technology-related concepts of thermostats to behavior studies. The figure exemplifies the concepts, which can be used while applying a STC approach to discuss smart thermostats.

In summary, both behavior and innovation studies can provide new perspectives for a better understanding of behavior based innovations, like smart thermostats, smart meters and gamification-based interventions. The term ‘behavioral capital’, which refers to “latent potential of behavioral change to affect improvement in environmental quality” by means of “behavioral innovations”,

may help here. It compares the quality of products and services by referring to their behavior and innovation related origins [80]. Being proven to be more effective and less capital-intensive than purely technology-based innovations for sustainable development, behavior-aware innovations can trigger behavior change in order to create value for both environmental impact and financial profit. Thus, for the sake of competitiveness, establishing a dynamic B&I model or theory in the design and development process of a product or service may help as much as embedding an algorithm to the gadget for behavior modeling, as is usually done with the today's gadgets and tools. On the other hand, this approach can have even higher impact if the transdisciplinary point of view is followed, which would facilitate the interactions between researchers from distinct fields and other relevant actors, like policy makers, investors and educators.

6. Concluding Remarks

6.1. Discussions

Similar to the most of the resource efficiency and sustainability technologies, those for the building energy efficiency should be innovative and behavior dependent by design and should provide new ways of practicing energy use. However, the domain-specific B&I studies limit the potential for comprehensive and effective conceptualizations. Thus, these research fields should also be considered together to provide better insights and sustainable solutions regarding to transformation of energy use. By doing so, behavior studies can go beyond the research on determinants of occupant behavior whereas innovation studies can enlarge its scope to include more than market response and consumption patterns.

Not surprisingly, the B&I literature has already taken advantage of some similar paths, including theories, models and concepts. For example, both of them are mostly influenced from economic theories of rational choice (RCT and UT) at the beginning of their development phases, but then used behavioral economics to understand human decision making for energy efficient products (see Section 2.1) [130]. Similarly, there are studies in both B&I literature which deal with energy use as a social practice (See Sections 2.1.3 and 2.2.2). TRA was originally developed for behavior research but then transformed to TAM for innovation research (see Section 2.2). Social patterns and lifestyle have high influence on B&I-related responses of people and represented in certain theories of both (e.g., Lifestyle Theory of behavior studies and Theory of Economic Development of innovation studies) [56]. Moreover, evidence shows that better interaction among people can facilitate exchange of information and hybridization of ideas. This is one of the most important drivers of both behavior change and innovation diffusion [125]. Thus, both literature paid attention to learning mechanisms and types: this is discussed in behavior literature as social learning (see Section 2.1.2) and in innovation literature as interactive learning [56].

Beside these limited theoretical agreements, there are also few empirical studies to use some hybrid conceptualizations. The term '*behavior diffusion*' is used in the meaning of innovation diffusion of behavior based energy technologies which would have both positive (efficiency) or negative (rebound) effects [110]. The agent-based simulations to evaluate the impact of heating feedback devices on energy consumption as done by Jensen et al. show how to facilitate the role of these technologies for behavior diffusion [110]. Some eco-innovations at the late stages of diffusion are also seen to have potential benefits of overcoming existing barriers related to customers purchasing and using preferences [12] and this mutuality underpins the continuous evaluation for behavior concerns for energy innovations. Further, energy behavior based consumer participation and support for leveraging environmental sustainability potential of technological innovations in building (social housing) retrofit projects is discussed in [64]. It is obvious that the B&I research domains are able to explain some common or interrelated phenomenon mostly with their own methodologies and terminologies. Only for limited number of topics they overstep disciplinary isolation instead of using collaborative approaches. These theoretical and empirical accomplishments show that as the systemic conceptualizations and

empirical methodologies for transdisciplinary research are developed, behavior aware energy efficiency innovations may appear more frequently.

These few theoretical agreements and empirical studies show the benefits of collaboration between B&I studies. However, there are further benefits to be gained from an interdisciplinary dialog between B&I studies in order to establish powerful links between society and technological innovations. For energy efficiency in built environments, they include (i) making a success of irrationalities embedded in human behavior (not only economic but also psychological) for better interventions, (ii) leveraging design and interactivity of building energy systems for easier adoption, (iii) a better understanding of roles of intermediary actors and dynamics of driving factors for the transition in energy infrastructure and culture, (iv) proposing dynamic behavioral interventions adaptive to rate of diffusion of an regulatory or technological innovation. These benefits can best be achieved with a holistic and dynamic point of view that can synthesize the related concepts of B&I studies in order to bridge the gap between human and technology dimensions for a given problem.

This paper aims to facilitate systemic interaction between B&I studies and clarify the interplay between occupants and building energy efficiency systems. It provides a thorough discussion of the current state-of-the-art on conceptualizations, theories and models of the B&I literature in the building energy efficiency research (Section 2) and presents an overview of interdisciplinary dialog between these research fields (Section 3). Being an active research field for more than 50 years, behavioral energy efficiency has domain-specific fragmentation of economical, psychological, sociological, and integrated (combinations of former three) theories. The models developed from such theories are capable of providing theoretical and empirical conceptualizations to understand decision making of individuals and society and to design behavior change programs. On the other hand, innovation studies have conceptualizations for acceptance, adaption, diffusion and social interaction of energy efficient building technologies. Despite being closely related to both human and technology dimensions of building energy efficiency, there is only a limited interaction among the concepts of B&I research (Section 3). However, the collaboration of B&I literature can provide necessary conceptualizations to establish more effective links between human and technology dimensions of building energy efficiency research. Thus, in order to leverage the interdisciplinary dialog between B&I studies, we used a conceptual framework, namely SCT, in this study. The potential contributions of B&I studies to each other are discussed in Section 4. These contributions can help to develop behavior-aware technological innovations and shows the potential directions or transdisciplinary research for energy efficiency in built environments. Since there is not any previous attempt to systematically interweave B&I studies as we intended, we provided a hypothetical exemplification for thermostats in Section 5 in order to clarify the benefits of an interdisciplinary approach.

6.2. Future Work

Future research should focus on leveraging interdisciplinary dialog between B&I studies and on creating a transdisciplinary framework in the field of building energy efficiency. Fueled with experiences in several EU-funded projects [131–133], as well as teaching background for technology-society relationship for a long time, the initial step to reach this goal is to develop models or frameworks. This can put the ‘socio-technical core’ conceptualization into practice. The second step is to integrate these models into ongoing research activities that will help to develop new solutions based on cyber-physical systems for energy efficiency in built environments. These solutions aspire to deliver energy efficiency and personalized comfort conditions in tandem and will be reported in a future study.

To make this synthesis possible, technological developments are accompanied with B&I-related concerns from the very beginning of research. With the integration of models or frameworks, there will be more systematic interactions between human factor and technological developments, in parallel to targets of STC conceptualization. As we gain experience in these processes, in the third step, we will

develop educational and policy tools that can facilitate transdisciplinary research for behavior-aware sustainability innovations.

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Appendix A. Steps Followed while Creating Original Dataset and Visualizing Network Analysis

In order to filter out a database which is relevant to behavior and innovation studies in the building energy efficiency domain from WoS (excluding renewables domain), a special set of keyword configuration is created based on reviews in Section 2:

TITLE: (energy OR electricity OR heating OR cooling OR lighting OR appliance*)
AND
TITLE: (efficien* OR saving* OR reduction OR consum* OR use* OR demand)
AND
TITLE: (building* OR house* OR home OR residential OR non-residential OR office OR commercial)
AND
TOPIC: (behavio* OR socio* OR social OR pro-environmental OR pro-social OR eco-* OR habit OR occupa* OR culture
OR theor* OR model OR learning OR practice OR network OR motivation OR lifestyle OR responsibility OR
interpersonal)
AND
TOPIC: (innovati* OR adaption OR adoption OR diffusion OR acceptance OR social practice OR barrier* OR driver* OR
transition* OR niche OR technolog*)
NOT
TOPIC: (renewable* OR PV OR photovoltaic OR wind)

Here, *TITLE* and *TOPIC* terms show the parts of an article in which search engine is looking for entered terms (*TOPIC* includes title, abstract, original keywords and the new ISI keywords). Also, the * sign lets search engine to include several alternatives of words derived from same root (e.g., occupancy, occupant and occupation). Since some of the terms (like ‘energy’, ‘behavior’ and ‘use’) are commonly used in material and mechanics research as well, we filtered out potentially relevant WoS categories like Energy Fuels, Construction Building Technology and Social Sciences Interdisciplinary (full list of categories is given in Table A1). Using the terms combination and category selection given above, we obtained a dataset with 973 recordings. Moreover, articles found by this initial search are manually controlled by using their titles via WoS web interface. In the end, after the elimination of irrelevant and identical entries, there were 737 unique entries. Once the original dataset of the survey is created, it is downloaded as several files (WoS doesn’t allow to download files more than 500 items) in ISI flat format and merged manually to a single file. Then, a detailed analysis is performed as explained below by using software called Sci2 and the related visualizations are created by softwares Gephi and EPS\PS viewer [74,134,135].

In order to find out the key concepts facilitating the relationship between behavior and innovation studies in the field of building energy efficiency, we used the word co-occurrence analyser of Sci2 software. We searched for highly frequent words and phrases placed in the ‘Abstract’, ‘Title’, ‘Original keywords’ and ‘New ISI keywords’ columns of original database and assessed their co-occurrences. After filtering elements with less than three occurrences, we are left with 362 terms (words or phrases).

Then, the loosely relevant (e.g., wall, software, etc.) or highly general elements (e.g., ‘energy’, ‘efficiency’, ‘consumption’, etc.) were manually eliminated; following this, the similar or identical (e.g., ‘adaption’ and ‘adoption’) entries were merged. After these processes, the data set was a network composed of 38 nodes and 179 edges. These nodes were categorized manually (behavior, innovation and commons) by referring to papers used for keyword selection and following these criteria:

- i If a term belongs to theoretical core of the one of the behavior or innovation theories, it is assigned to the category of corresponding literature (e.g., the term ‘diffusion’ is assigned to innovation studies category),
- ii If a term is specifically discussed in reviews of one of the behavior or innovation literature but not discussed in the other, the term is assigned to one that discusses it (e.g., SPT is assigned to behavior literature),
- iii If it is clear that a term is more frequently used by one of the candidate literature, it is assigned to that category (e.g., the terms ‘attitude’ and ‘norm’ is assigned to behavior studies category)
- iv If a term is frequently used by both research fields, it is assigned to commons category (as the term ‘barriers’ is assigned to commons category).

Then, the next step was the preparation of network representations. In order to provide more insights, node size attribute is set to betweenness centrality and label size attribute is set to total reference to each term in original database. Here, we used the built-in tools of the Gephi software.

In the second part of the analysis, using the database of this network and manually eliminating the internal links in categories, we created a bipartite graph on Sci2 and visualized it in EPS\PS viewer to obtain a leaner representation of the interactions (innovation and commons are grouped together for convenience).

Table A1. List of WoS categories chosen in creating the original dataset.

Energy Fuels
Construction Building Technology
Social Sciences Interdisciplinary
Engineering Civil
Environmental Sciences
Environmental Studies
Multidisciplinary Sciences
Green Sustainable Science Technology
Economics
Planning Development
Engineering Electrical Electronic
Engineering Environmental
Thermodynamics
Business Finance
Computer Science Information Systems
Engineering Mechanical
Sociology
Computer Science Interdisciplinary Applications
Engineering Industrial
Architecture
Automation Control Systems
Psychology
Psychology Applied
Management
Psychology Multidisciplinary
Business
Operations Research Management Science
Ecology
Philosophy
Engineering Multidisciplinary
Political Science
Social Issues

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