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A multidisciplinary research approach to energy-related behavior in buildings

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1. Abstract

A multidisciplinary research approach to energy-related behavior in buildings

Occupant behavior in buildings is one of the key drivers of building energy performance. Closing the “performance gap” in the building sector requires a deeper understanding and consideration of the “human factor” in energy usage. For Europe and US to meet their challenging 2020 and 2050 energy and GHG reduction goals, we need to harness the potential savings of human behavior in buildings, in addition to deployment of energy efficient technologies and energy policies for buildings. Through involvement in international projects such as IEA ECBC Annex 53 and EBC Annex 66, the research conducted in the context of this thesis provided significant contributions to understand occupants’ interactions with building systems and to reduce their energy use in residential and commercial buildings over the entire building life cycle.

The primary goal of this Ph.D. study is to explore and highlight the human factor in energy use as a fundamental aspect influencing the energy performance of buildings and maximizing energy efficiency – to the same extent as technological innovation.

Scientific literature was reviewed to understand state-of-the-art gaps and limitations of research in the field. Human energy-related behavior in buildings emerges a stochastic and highly complex problem, which cannot be solved by one discipline alone. Typically, a technological-social dichotomy pertains to the human factor in reducing energy use in buildings. Progressing past that, **this research integrates occupant behavior in a multidisciplinary approach that combines insights from the technical, analytical and social dimension.** This is achieved by combining building physics (occupant behavior simulation in building energy models to quantify impact on building performance) and data science (data mining, analytics, modeling and profiling of behavioral patterns in buildings) with behavioral theories (engaging occupants and motivating energy-saving occupant behaviors) to provide multidisciplinary, innovative insights on human-centered energy efficiency in buildings.

The systematic interconnection of these three dimensions is adopted at different scales. The building system is observed at the residential and commercial level. Data is gathered, then analyzed, modeled, standardized and simulated from the zone to the building level, up to the district scale. Concerning occupant behavior, this research focuses on individual, group and collective actions. Various stakeholders can benefit from this Ph.D. dissertation results. Audience of the research includes energy modelers, architects, HVAC engineers, operators, owners, policymakers, building technology vendors, as well as simulation program designers, implementers and evaluators. The connection between these different levels, research foci and targeted audience is not linear among the three observed systems. Rather, the **multidisciplinary research approach to energy-related behavior in buildings** proposed by this Ph.D. study has been adopted to explore solutions that could overcome the limitations and shortcomings in the state-of-the-art research.

1.1. Extended Abstract (English)

This thesis embraces studies on energy-related occupant behavior (OB) – including opening/closing windows, adjusting thermostats, turning on/off HVAC systems, pulling up/down blinds, switching lights, operating plug loads, and electrical equipment. The objective of this dissertation is to link building physics (occupant behavior simulation in building energy models) and data analytics (occupant modeling) to behavioral theories (user engagement) to provide multidisciplinary, innovative outcomes on human-centered energy efficiency in buildings.

A methodological approach is adopted – as fil rouge connecting the three years of research – to provide innovative answers to a collection of unresolved questions on occupant energy-related behavior in buildings.

Building occupants play a critical but poorly understood the role in the built environment. To face climate changes and aggressive energy reduction goals, technology driven solutions alone are necessary but insufficient. Energy-related behavior is individual and stochastic, rather than recursive, reasoned or predictable. Moreover, buildings are not passive containers of the occupants, rather active systems that interact dynamically with them. In the modern building physic domain, developing an advanced level of building energy-efficiency literacy grounded on the human factor in building energy use is foreseen as a stage for bridging the actual credibility gap of energy-efficiency in buildings. Despite the research community having made substantial efforts to sharpen and increase the understanding of occupant behavior in buildings, significant inconsistencies between estimated and real building performance still exist. The proposed research methodology is based on the core concept that the issue of the human factor in building energy use is a highly complex problem, which cannot be fully understood or solved by one discipline alone – as is the typical approach of current research in the field.

Going beyond the actual technological-social dichotomy of occupant behavior in building physics, this Ph.D. dissertation combines insights from the technical, analytical and social dimension of energy-related occupant behavior in buildings. To meet this goal, the three years of research conducted under the framework of this dissertation adopted a multidisciplinary approach bringing occupant behavior research in the loop of the building, data, and human systems.

This Ph.D. dissertation is structured as an assemblage of research outcomes aiming to illuminate innovative information, knowledge, solutions and insights to bridge the limitations of current research on the topic of occupant behavior in buildings. Conventional research's limitations and deficiencies of research are here summarized as entrenched in:

1. *Oversimplified or omission of occupant behavior information throughout the building operation process*
2. *Lack of effective analytic techniques providing useful knowledge on occupant behavior in buildings*
3. *Absence of agreement on validity and effectiveness of occupant behavior modeling and simulation approaches in building energy models (BEMs).*
4. *Gap between predicted (or modeled) energy consumption and actual building energy consumption due to a lack of adequate behavioral inputs in building energy simulation*
5. *Lack of practical solutions and insights to leverage energy saving potential of the human factor in building energy usage*

Concerning the limits of the current body of research, this thesis explores occupant behavior to raise some unresolved research questions, that to be addressed:

1. *How to study occupant behavior based on facts and not hypotheses?*
2. *How to translate building and human information into useful knowledge?*
3. *Which are the strengths, shortcomings, and needs of the modeling and simulation methodologies?*
4. *Is there sufficient benefit in quantifying occupant behavior in building energy simulations?*
5. *How to engage the human operator into optimized control formulation in buildings efficiently?*

Accordingly, the research conducted in the context of this thesis aims to overcome shortcomings, limitations, and challenges of the current state of the art alternatives, by analyzing innovative approaches in the field of energy-related occupant behavior:

1. Sensing
2. Analytics
3. Modeling
4. Simulation
5. Engaging

Consequently, the research outcomes of the thesis focus on:

1. Provide information on the building-human interaction via observation studies (sensing).

A review of the state of the art achievements and gaps of techniques and methodologies in the observation of energy-related behaviors is conducted. This covers adaptive actions – occupant changes that alter the environment to make it more comfortable (thermal, air quality, light, noise), including window-opening behavior, usage patterns of thermostat or air conditioning – and non-adaptive actions: operation of lighting and appliances and occupant presence and movement into indoor spaces. Transversal questionnaire surveys emerged useful tools to gain information on general behavioral patterns and drivers, and to find connections between human, social and local comfort parameters. Based on an extensive literature review, gaps were identified, and guidance was given for future survey studies. It was concluded that insights from social practice theories and techniques must be acquired to deploy robust and unbiased questionnaire results, which will enable to gain new, more comprehensive knowledge in the field and to compare energy-related occupant behavior in office buildings among different cultures, climates, and countries.

2. Discover knowledge on the human factor in building energy use through energy-related behavior data analytics and model standardization.

Data mining techniques are applied to discover behavioral patterns and profiles. Three analytic studies are presented, utilizing the Knowledge Discovery in Database (KDD) methodology. In the first exploration study, a framework is suggested as an improvement of the notion of the window opening behavioral patterns not only as merely statistical relevant clusters but as also incorporating the driver-response conditioning dimension with typical occupant's habits in offices. Secondly, a data mining structure is established to extrapolate information on occupancy schedule patterns in offices, from measured building big data streams. Thirdly, a methodology for discovering the impact of socio-demographic variables influencing building energy consumption and penetration of retrofit measures at the district level is proposed.

With respect to modeling the stochastic nature of human behaviors, a critical review of the existing energy-related occupant-modeling concepts published in literature has been conducted as part of the Ph.D. studies. Examples of each model type predicting: a) the states of the building components and b) the event (state transitions) of the building components are described. The critical analysis of existing modeling approaches and a discussion of empirical and simulation outcomes of the research lead to the conclusion that direct discrete-event models overcome a wide array of weaknesses emerged among the other modeling approaches.

Moreover, a critical review of simulation methods of behavioral models adopted by the research community has been carried out. A deficiency of a standardized method for describing and implementing energy-related models of occupant behavior in building simulation tools emerged. Without an universal agreement on a technical structure, simulation results become difficult to compare, to impede the research community to attain general validity of simulation outcomes. A standardized language to represent and communicate OB models in building energy simulation is hence needed. A homogeneous semantic information model for the representation of occupant behavioral models that enable interoperability of inputs and transferability of simulation outputs is developed. Based on extensive reviews of more than 130 journal articles publishing energy-related behavioral models and studies, an ontology framework is designed to provide the research community with a distinctive systematic approach to describing the energy-related behavior phenomena in buildings, based on Driver, Need, Action and Systems (DNAs). Grounded on the DNAs framework, a

standardized eXtensible Markup Language (XML) schema is adopted to represent OB models (obXML) in building energy models. The obXML syntax has the intrinsic flexibility to represent different types of occupant behaviors in buildings, and it has the capability to be expanded to incorporate an increasing number of categories of actions.

3. Provide insights via dynamic building energy simulations applying behavioral models to improve the accuracy of energy building performance prediction. Two studies are presented.

A residential model implemented two stochastic behavioral models for window opening and closing behavior and the usage of thermostats. These models differentiated among active, medium and passive users, to highlight variations in heating consumption at the dwelling level, due to diverse energy intensive behavioral patterns.

An office building energy model employed behavioral models published in the literature for window opening behavior, usage of heating and fan systems as interaction with blinds. The scope of the simulation study was to test the robustness of energy-related interaction with building components and control systems over different building envelope design and climate conditions.

4. Provide energy saving solutions adopting user engaging techniques and behavioral theories

Two studies are presented. A pilot study tested the effectiveness of a smart monitoring system in reducing domestic electricity consumption by engaging householders towards energy-savings behaviors. The conducted study combined an energy visualization and feedback dashboard with a persuasive communication campaign providing tailored peer-compared information and advice for reducing energy usage.

Differently from the residential sector, when engaging occupant behavior in working environments, it is necessary to achieve a deeper understanding of the motivation structure within the complexity of different social groups driving behavior. Accordingly, a motivational survey framework was developed to gain insights on collective and social conventions of energy-related behavior, shaped by geographical and climatic contexts, culture and norms.

Without the presumption of entirely covering the broad knowledge of the building, data, and behavioral sciences, the research activities have been conducted with a rigor driven by formal academic education in the field of architectural engineering, advanced studies of data mining and statistics analysis methods, and critical analysis of behavioral campaign strategies. The systematic interconnection of the three dimensions was adopted at different scales. The building system was observed at the residential and commercial level. Data was gathered, analyzed, modeled, standardized and simulated from the zone to the building level, up to the district scale. Concerning occupant behavior, research focuses on individual, group and collective practices.

Key takeaways and benefits to the research arena provided by this Ph.D. dissertation have conversed.

The thesis strives to illuminate how the multidimensional approach triangulated from the building-data-human systems to study energy-related behavior in buildings will enhance the state of the art to provide advancements in energy efficiency - to the same extent of technology innovations in the construction sector. This research aims to set the stage for occupant behavior in building to be a central part of the innovation paradigm for energy efficiency of the built environment. Specifically, it exploits the potential of significant energy conservation opportunities, by integrating occupants in-the-loop of building design, sensing, and control, as well as with the help of behavioral awareness as an energy efficiency measure in buildings. Outcomes of energy scenarios include quantification of occupant behavior impacts, such as the potential for energy savings and hidden energy and comfort drawbacks. These will support building energy designers, modelers, operator and managers to develop specific energy efficiency measures, and to evaluate technology adoption levels, by taking into account the importance of building occupants. Also, the knowledge discovered aims to support energy and urban planners to the improvement of more informed energy policies, programs, codes and standards and the development of robust energy planning tools targeting human-centered and low-cost investment energy efficiency in buildings. Challenges and future steps of the presented dissertation will aim to translate the research insights into practical deployment solutions having measurable impacts on individual, group and collective behaviors. Scalability of energy efficiency behavioral solutions is foreseen from the building zone to the building level, up to the urban scale.

1.2. Extended Abstract (Italian)

Approccio multidisciplinare alla ricerca sul comportamento dell'occupante negli edifici

Le indagini di dottorato si compongono come prosecuzione delle ricerche sul tema “Influenza del comportamento dell'utente negli edifici” iniziate con la tesi magistrale nell'ambito del progetto Annex 53 “Total Energy Use in Buildings: Analysis & Evaluation Methods” dell'IEA – International Energy Agency” (IEA EBCP 2013). L'attività di ricerca condotta nell'ambito di questa tesi di dottorato si riferisce al triennio 2013 –2016, nell'ambito dell'Annex 66 “Definition and Simulation of Occupant Behavior in Buildings” – progetto dell'IEA totalmente dedicato alla definizione e simulazione del comportamento dell'occupante negli edifici.

La presente tesi di dottorato è strutturata come un assemblaggio di risultati della ricerca, avente obiettivo la messa in evidenza di soluzioni innovative capaci di dare risposte in ambiti irrisolti dallo stato dell'arte della ricerca.

La tesi adotta un metodo multidisciplinare nello studio del comportamento dell'occupante negli edifici e del suo impatto sulla performance energetica dell'edificio (consumi energetici e IEQ), riferendosi ad ambiti scientifici dell'architettura, fisica dell'edificio, ICT e scienze sociali. Scopo finale della tesi di dottorato è la formulazione di un approccio sistemico alla ricerca, triangolato dall'analisi di dati, comportamento dell'edificio e comportamento dell'occupante, capace di provvedere innovazione nell'ambiente costruito, al medesimo livello d'interventi meramente tecnologici.

La tesi si focalizza sullo sviluppo di metodologie d'indagine e la presentazione di risultati della ricerca in cinque settori fondamentali: monitoraggio, analisi, modellazione, simulazione e sensibilizzazione del comportamento energetico degli occupanti in edifici residenziali e per uffici.

In questo contesto, la tesi affronta nello specifico i settori identificati, nel tentativo di fornire risposte – supportate da risultati concreti della ricerca – ai seguenti quesiti:

- Monitoraggio: come osservare l'interazione uomo-edifici in conformità a fatti e non ipotesi?
- Analisi: come trasformare i dati di monitoraggio dell'interazione occupante-edificio in informazioni utili al conseguimento di strategie di progetto e controllo energeticamente efficienti?
- Modellazione: quali sono gli attuali punti di forza e debolezze dei metodi di modellazione stocastica del comportamento dell'utente?
- Simulazione: quali sono i benefici e gli attuali limiti dell'implementazione di modelli stocastici di occupante in programmi di simulazione energetica dinamica?
- Sensibilizzazione: come integrare i risultati della ricerca in strategie di comunicazione persuasiva efficaci e ottimizzare logiche di controllo e d'interazione occupante-edificio?

Contenuti

Al fine del raggiungimento degli obiettivi di riduzione del consumo energetico nel settore edilizio al 2020 e 2050 – la comunità scientifica richiede modelli e strumenti capaci di descrivere la prestazione energetica reale degli edifici. Nonostante i notevoli passi avanti nell'ambito della simulazione energetica dinamica degli edifici, tale rappresentazione emerge ad oggi ancora distante dall'effettivo consumo energetico e dai livelli di qualità ambientale osservata in ambienti indoor. Numerosi studi dimostrano che – tra le innumerevoli variabili responsabili di tale “divario di credibilità” (Bordass et al. 2004) nelle attuali ricerche, il comportamento degli occupanti assume una rilevanza di primo rilievo. Il concetto fondamentale risiede nella nozione che “gli occupanti usano l'energia, non gli edifici” (Janda, 2011).

Attraverso il coinvolgimento in progetti dell'International Energy Agency, quali l'Annex 53 e a seguire l'Annex 66, questa tesi di dottorato dedica uno sforzo speciale alla comprensione delle interazioni tra gli occupanti e i sistemi di controllo della prestazione energetica degli edifici e allo sviluppo di strategie comportamentali e a basso contenuto tecnologico, che permettano di migliorare il rendimento energetico degli edifici, senza compromettere i requisiti di comfort ambientale per gli occupanti medesimi. Il comportamento energetico degli occupanti si riferisce a meccanismi di adattamento alle condizioni ambientali degli ambienti indoor (de Dear and Brager). Questi afferiscono all'interazione degli occupanti con i sistemi impiantistici di raffrescamento, riscaldamento, illuminazione, ventilazione e uso di apparecchiature elettriche, attraverso i terminali impiantistici di controllo (termostati, valvole termostatiche, controllo manuale di accensione e spegnimento di apparecchiature elettriche e sistemi d'illuminazione) e l'interazione con l'involucro edilizio (apertura/chiusura finestre, utilizzo di schermi solari). Inoltre, la ricerca si focalizza sull'influenza di meccanismi non-adattativi, quale la presenza e il movimento degli occupanti negli spazi confinati. Le interazioni occupante-edificio sono valutate negli edifici residenziali così come in edifici commerciali per uffici.

Obiettivo della tesi è l'integrazione del comportamento umano con i sistemi energetici dell'edificio a servizio dell'intero ciclo di vita dell'edificio: dalla fase di costruzione e di progettazione, al funzionamento operativo, e nelle fasi di retrofit. Fine ultimo è il raggiungimento di edifici ad energia quasi-zero, intelligenti ed economicamente ottimizzati. In questa prospettiva, la presente tesi fornisce gli strumenti necessari per valutare scenari di rendimento energetico previsto che – con un adeguato margine di sicurezza – valutino l'incertezza, i rischi e il potenziale di risparmio energetico di tecnologie ad alta efficienza energetica dal punto di vista della natura stocastica del comportamento umano negli edifici.

La comprensione del fattore umano nel consumo energetico degli edifici è un tema altamente complesso e controverso, che difficilmente può essere raggiunta attraverso analisi settoriali indipendenti. Andando oltre il tradizionale approccio dicotomico tecnologico-sociale adottato dalla letteratura scientifica attuale, la presente tesi di dottorato si compone intorno alla triangolazione di conoscenze empiriche, tecniche e strumenti di ricerca di diversi settori multidisciplinari. Questi afferiscono al settore della fisica tecnica ambientale, a metodi di data mining e di analisi statistica dei dati d'interazione uomo-edificio e a teorie e tecniche di sociologia, psicologia comportamentale e di comunicazione persuasiva. È in quest'ottica che la presente tesi intende fornire risultati innovativi e in materia di efficienza energetica incentrata sull'interazione uomo-edificio, al pari d'interventi strutturali ad alto grado d'investimento economico a favore dell'innovazione tecnologica per l'ambiente costruito.

In questa prospettiva, la missione di questa tesi è lo sviluppo di un approccio multidimensionale allo studio del “fattore umano” del consumo energetico negli edifici. Sebbene la presente tesi non si ponga l'ambizione di coprire completamente la vasta conoscenza pertinente alle arene scientifiche dei diversi ambiti disciplinari, l'approccio multidisciplinare proposto è stato applicato con rigore scientifico, guidato da una formazione accademica nel settore dell'architettura e della fisica dell'edificio, studi avanzati di data mining e di metodi di analisi statistica e meticoloso esame critico della letteratura socio-psicologica di teorie comportamentali, e di applicazione pratiche di campagne di comunicazione persuasiva.

Questa tesi si propone di fornire un approccio metodologico multidisciplinare per incontrare le richieste della comunità scientifica internazionale nell'ambito di soluzioni efficaci per l'osservazione e la misura dell'interazione uomo-edificio, l'analisi dei dati di monitoraggio, la modellazione della variabile stocastica del comportamento umano, la standardizzazione delle procedure d'implementazione di modelli comportamentali nelle simulazioni energetiche dinamiche degli edifici, nonché la traduzione dei dati, modelli e simulazioni in soluzioni per la sensibilizzazione degli occupanti verso comportamenti energeticamente efficienti.

Rispetto allo stato dell'arte delle attuali ricerche, la presente tesi di dottorato propone revisioni critiche, complete ed aggiornate delle attuali tecniche di raccolta dati, di modellazione stocastica e simulazione energetica dinamica. Soluzioni innovative nei metodi di raccolta d'informazioni da dati comportamentali e d'interazione con i sistemi di controllo, attraverso questionari longitudinali a scala internazionale, sono proposte al fine di colmare le lacune emerse dall'analisi dello stato dell'arte. Tecniche di data mining sono applicate con l'obiettivo di tradurre in maniera diretta e automatica notevoli quantità di dati di monitoraggio in modelli comportamentali e profili di occupazione. La descrizione del comportamento energetico dell'occupante negli edifici è mostrata nella presente tesi da un quadro ontologico nominato DNAs (Driver – Need – Action – Systems). Tale ontologia costituisce la traduzione in termini ingegneristici della risposta cognitiva dei fenomeni di adattamento degli occupanti negli edifici. Inoltre, questa disegna la base fondante per l'adozione di una sintassi standardizzata (in linguaggio XML) capace di rappresentare una libreria completa (obXML) dei modelli di comportamento degli occupanti aventi impatto sugli usi finali di energia negli edifici. Modelli comportamentali descritti secondo questo linguaggio standardizzato assicurano validità e trasferibilità dei risultati, anche quando implementati in diversi programmi di simulazione energetica dinamica.

Infine, facendo leva su una più efficace comunicazione tra i sistemi edificio-impianto-occupante, i risultati di questa tesi di dottorato sono applicati per favorire la maturazione di comportamenti degli utenti e di politiche di controllo, gestione e riqualificazione edilizia in maggior misura energeticamente consapevoli. Sfide e futuri passi della presente tesi di dottorato avranno lo scopo di tramutare i risultati della ricerca in applicazioni efficaci, aventi impatto misurabile sul comportamento individuale e collettivo degli occupanti, al fine ridurre il divario di credibilità tra efficienza energetica prevista e reale in edifici residenziali e commerciali, dalla scala dell'edificio al livello di conglomerato urbano.

Risultati raggiunti

I risultati di questa tesi di dottorato hanno l'obiettivo di colmare l'attuale divario tra efficienza presunta e reale nel settore edilizio, attraverso il consolidamento e l'avanzamento in metodologie e tecniche di osservazione, analisi dati, modellazione stocastica del comportamento dell'occupante, implementazione in programmi di simulazione energetica dinamica e sviluppo di campagne di comunicazione persuasiva e strategie di controllo ottimizzato dell'interazione uomo-edificio.

La metodologia e le procedure proposte da questa tesi di dottorato sono state adoperate come base fondante del progetto Europeo H2020 MObistyle: *"MOtivating end-users Behavioral change by combined ICT based tools and modular Information services on energy use, indoor environment, health and lifestyle"* (2016-2019).

L'obiettivo generale di MOBISTYLE è di motivare, attraverso un approccio multidisciplinare al progetto, il cambiamento del comportamento degli occupanti, aumentando la consapevolezza dei consumatori all'uso di energia ed alla salubrità degli ambienti indoor. Attraverso l'impiego di piani di monitoraggi ambientali e personalizzati basati sull'innovazione tecnologica in campo ICT, e l'inclusione pro-attiva ed iterativa degli occupanti nei processi di interazione con il sistema edificio-impianto, il progetto si pone l'obiettivo di fornire benefici misurabili in termini di riduzione del consumo energetico, aumento dei livelli di comfort ambientale, oltre che un miglioramento del livello di salute e dello stile di vita, anche al di fuori dell'ambiente domestico e/o lavorativo.

I risultati della ricerca sono supportati da un'ampia attività di pubblicazione in riviste internazionali di settore (Energy and Building, Building and Environment, Journal of Building Performance Simulation, Building Simulation Journal, Energy Research and Social Science, Applied Energy) e dalla partecipazione a Conferenze di rilevanza internazionale nel panorama della ricerca della fisica tecnica ed ambientale. Qui di seguito si riporta un elenco della produzione scientifica inerente alla presente tesi di dottorato.

La ricerca di dottorato proseguirà in un Post-Doctorate presso il Simulation Reserach Group della Energy Technology Area del Lawrence Berkeley National Laboratory, Berkeley (USA) a partire da Luglio 2016.

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1. **S. D'Oca**, S.P. Corgnati, V. Fabi, R.K. Andersen, *Effect of thermostat and window opening occupant behavior models on energy use in homes*, Building Simulation – 2014, DOI:10.1007/s12273-014-0191-6, vol. 7, Issue 6, pp. 683-694, ISSN: 1996-3599
2. **S. D'Oca**, S.P. Corgnati, T. Buso, *Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings*, Energy Research & Social Science – 2014, vol. 8, pp. 131-142, ISSN 2214
3. **S. D'Oca**, T. Hong. *A data-mining approach to discover patterns of window opening and closing behavior in offices*. BUILDING AND ENVIRONMENT 11/2014; 82. DOI:10.1016/j.buildenv.2014.10.021
4. **S. D'Oca**, T. Hong. *Occupancy schedules learning process through a data mining framework*. ENERGY AND BUILDINGS 02/2015; 88. DOI:10.1016/j.enbuild.2014.11.065
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10. **S. D'Oca**, H.B. Gunay, S. Gilani, W.L. O'Brien, V. Fabi, S. Corgnati, A. Mahdavi. *A review of the occupant modeling approaches in offices with illustrative examples*. Submitted to JOURNAL OF BUILDING PERFORMANCE SIMULATION – June 2016
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12. V. Fabi, **S. D'Oca**, R.K. Andersen, S.P. Corgnati. *Influence Of Window Opening And Closing Behaviour and Heating Set-Point Adjustments on Heating Energy Consumption in Dwellings*. Proceedings of CLIMA 2013 - 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, Prague; 06/2013
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19. **S. D'Oca**, C. Delmastro, V. Fabi, S.P. Corgnati, *Testing Socio-Economic Demographic Variables on building energy consumption scenarios at the urban scale in Italy*, 8th Mediterranean Congress of HVAC – 2015, Juan-les-Pins, pp. 1-8
20. H.B. Gunay, W.L. O'Brien, I. Beausoleil-Morrison, **S. D'Oca**, S. Corgnati. *On modelling and simulation of occupant models*. Building Simulation Conference – 2015, Hyderabad, India – *Winning Best Paper Award IBPSA 2015*
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Chapter books – to be published

22. S. Corgnati, V. Fabi, **S. D'Oca** et al. REHVA Guidebook. Chapter 9. Behavior change – occupants' interaction with building automation and controls
23. S. Corgnati, F. Cotana, **S. D'Oca** et al. Cost-Effective Energy Efficient Building Retrofitting: Materials, Technologies, Optimization and Case Studies. Chapter 14 – A cost-effective human based energy retrofitting approach

1.3. Content organization. How to read this thesis.

This Ph.D. dissertation is structured as an assemblage of research outcomes aiming to bridge the limitations of current research on the topic of occupant behavior in buildings.

This dissertation advises innovative research to meet the actual international community enhancements in the field of:

1. **Sensing** techniques of the multidimensional sphere of human-building interaction
2. Improving occupant behavior data **analytics** and Knowledge Discovery in Databases (KDD)
3. Standardize occupant behavior **modeling** approaches for implementation in building simulation tools
4. Enriching outcomes of occupant behavior **simulation** in building energy models (BEMs)
5. Translating data, models and simulations into behavioral insights and solutions to **engaging** occupants into smart and energy-efficiency building-human interactions

The research conducted during the three years of the Ph.D. are curtailed as follows (Figure 1).

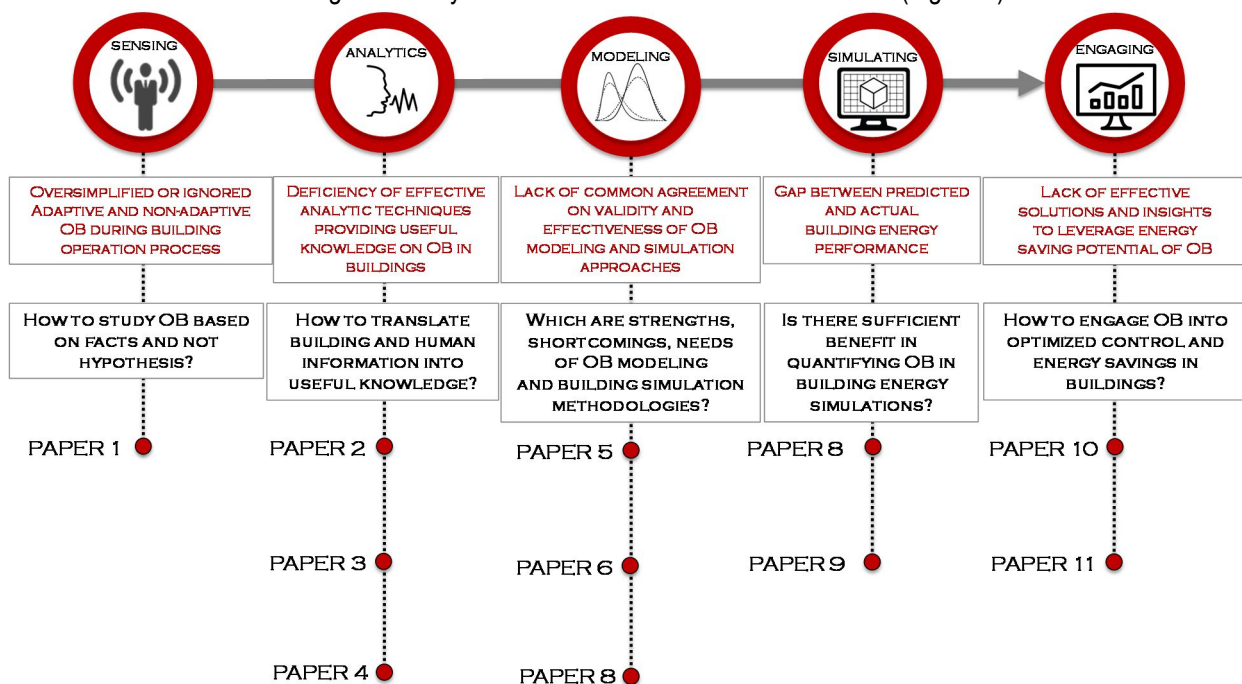


Figure 1. Schematic overview of current state of the art limitations of the key field of the occupant behavior investigation, their corresponding highlighted research questions and the vertical foci of research outcomes.

An **introduction** section is dedicated to the observation of actual state-of-the-art advances in international community research. Limits of the current investigations have been extensively analyzed as entrenched in:

1. Oversimplified or ignoring actual occupant behavior throughout the building operation process
2. Deficiency of effective analytic techniques providing useful knowledge on occupant behavior in buildings
3. Lack of common agreement on validity and effectiveness of occupant behavior modeling approaches
4. Gap between predicted and actual building energy performance, due to a lack of adequate behavioral inputs in building energy simulation
5. Lack of effective solutions and insights to leverage energy saving potential of occupant behavior on building energy usage

A **methodological** section focuses on applying multidimensional methodologies to fill gaps in information, knowledge, solutions and insights emerged in the exploratory phase. On the limits of the state-of-art research, the scope of this thesis researches on occupant behavior is to raise some unresolved research questions to be addressed, as follows:

1. *How to study occupant behavior based on facts and not hypotheses?*
2. *How to translate building and human information into useful knowledge?*
3. *Which are the strengths, shortcomings, and needs of the actual modeling and simulation methodologies?*
4. *Is there sufficient benefit in quantifying OB in building energy simulations?*
5. *How to engage the human operator into optimized control formulation in buildings effectively?*

A **result** section presents and discusses investigation approaches supported by a collection of peer-reviewed research outcomes, having a connection with key research topics, as described in Table 1.

A total number of 11 separated annexes (9 published and submitted journal articles and 2 conference proceedings) are provided, to deliver the reader with a detailed vertical focus on the research outcomes.

Table 1. The methodological research approach. Occupant behavior research grounds on focus, related innovation fields, and connection with research outcomes.

OB Focus	Innovation	Topic of research	Research Outcomes
SENSING	Information	Critical review and guidelines for OB Sensing techniques	Paper 1
ANALYTICS	Knowledge	KDD of window opening in commercial building	Paper 2
		KDD of occupancy in commercial building	Paper 3
		KDD of socio-demographic variables in block of buildings	Paper 4
MODELING		OB modeling approaches	Paper 5
		DNAs Framework	Paper 6
		obXML schema	Paper 7
SIMULATING		Solutions and Insights	BEM Simulation residential building
	BEM Simulation commercial building		Paper 9
ENGAGING	User engagement in residential buildings		Paper 10
	OB Survey Framework in commercial buildings		Paper 11

The research aims to provide innovation regarding **information** on occupant energy-related behavior in building through critical, updated and comprehensive reviews of the state of the art observation (data collection) studies, modeling, and simulation approaches.

Gathered information is hence translated into **knowledge**, thought advanced analytical methods – such as data mining techniques – to discover behavioral patterns and profiles in big building and behavioral data set. Standardization of such original knowledge is provided by means the definition of an ontology framework for energy-related behavior in buildings and the adoption of harmonized language to represent OB models in BEMs.

Finally, **solutions and insights** are provided through simulation studies, persuasive communication techniques, and technologies, as well as longitudinal surveys aiming at enhancing occupant driven energy efficiency in residential and commercial buildings.

Research outcomes of this dissertation are logically connected as illustrated in Figure 2.

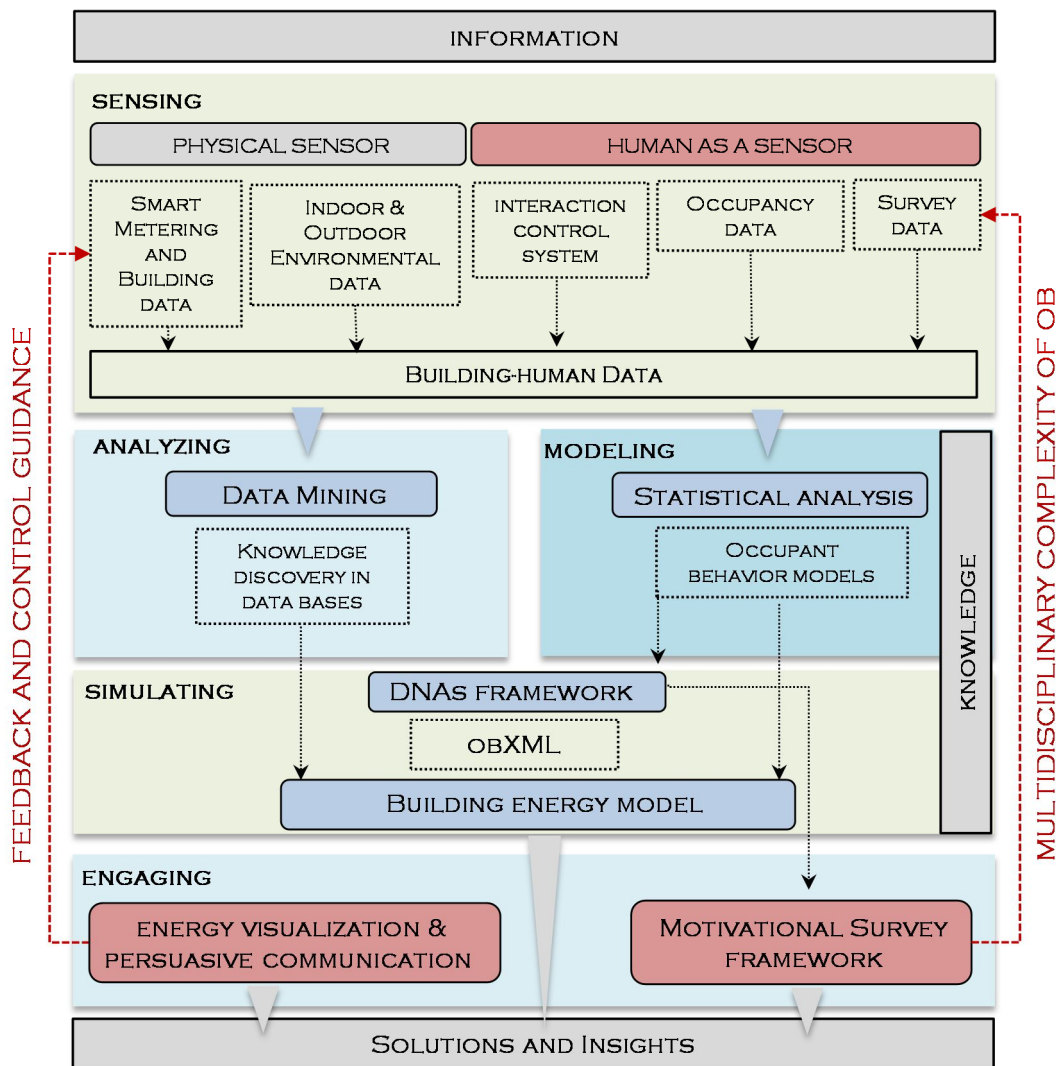


Figure 2. Schematic Overview of the dissertation research approach

Adequate sensing procedures of actual energy use and behaviors in building (monitoring techniques, surveys, etc.) establish the ground foundation of robust building-human data sets [Paper 1]. However, how to gain information on occupant behavior based on facts and not hypothesis is still an open question. Questionnaire survey emerged as optimal tools for discovery of a new layer of social, contextual and group interaction constructs related to driving forces and individual motivations.

Building and human information need to be translated into useful knowledge driving energy efficiency in buildings. Improved data analytics methods (data mining, statistical analysis) can lead to the development of advanced occupant behavioral models, patterns and profiles [Paper 2, 3, 4].

The strengths and shortcomings of the existing modeling approaches [Paper 5] must be carefully scrutinized. Among the simulation community, little agreement and understating on how to implement such behavioral models into current BEM simulation tools has been reached. Accordingly, behavioral model validity and transferability are sought by means the establishment of a common standardized framework among the international community, unfolding the cognitive dimension of occupant-human interaction through Drivers, Needs, Actions and Systems (DNAs) [Paper 6]. Grounded on the DNAs framework, a syntax (XML language) for representing a comprehensive library (obXML) of energy-related occupant behavior in buildings is established [Paper 7]. When implemented into current building simulation tools, validated behavioral models are supposed to develop energy prediction closer to reality [Paper 8, 9].

Finally, the knowledge gained must be employed to provide **solutions** and **insights** on how to engage the human operator into optimized control formulation in buildings effectively. Leveraging on improved communication on energy usage and IEQ between the building-data-human systems, behavioral science insights are applied to engaging energy-

aware behaviors in residential buildings [Paper 10]. However, engaging office users into comfort-adaptive and energy-saving behavior is grounded on diverse multidisciplinary drivers. A survey research framework is hence developed to provide quantitative descriptions on the collective and social motivations within the complexity of different social groups in working environment, under different geographical context, culture and norms [Paper 11].

A **conclusion** section focuses on emphasizing key takeaways provided to the research outcomes, as well as benefits provided to the research arena.

Bringing occupants in the loop of design, sensing, and control of buildings is foreseen as the way to provide advancements in energy performance and energy efficiency - to the same extent of technology innovations in the building sector. In a broader perspective, this Ph.D. dissertation aims to provide a standardized multidisciplinary methodological approach to enhance the state of the art on energy-efficient occupant behavior in the building sector and the field of building physics

The logical synopsis leading to the development of the dissertation is summarized as in Table 2.

Table 2. Logical synopsis of the methodological approach.

State of the art limit of research	Unabridged research questions	Innovations	Outcomes	Field of Research
Oversimplified or ignoring actual occupant behavior throughout the building operation process	How to study occupant behavior based on facts and not hypotheses?	Sensing the multidimensional sphere of human-building interaction	Analytical survey and guidelines of OB monitoring techniques OB survey framework and international questionnaire	OB Sensing
Deficiency of effective analytic techniques providing useful knowledge on occupant behavior in buildings	How to translate building and human information into useful knowledge?	Occupant behavior data analytics	Data mining techniques to discover patterns of energy-related building-human interactions in big data set	OB Analytics
Lack of common agreement on validity and effectiveness of occupant behavior modeling and simulation approaches	Which are the strengths, shortcomings, and needs of the actual modeling and simulation methodologies?	Occupant behavior modeling and simulation information standardization	Updated critical analysis and standardization tools of modeling and simulation approach for energy-related occupant behavior representation in buildings	OB Modeling
Gap between predicted and actual building energy consumption due to a lack of adequate behavioral inputs in building energy simulation	Is there sufficient benefit in quantifying OB in building energy simulations?	Occupant behavior simulation in BEMs	Simulation studies of energy-related occupant behavior in residential and commercial buildings	OB Simulation
Lack of effective solutions and insights to leverage energy saving potential of the human factor in building energy usage	How to engage effectively the human operator into optimized control formulation in buildings?	Translating data, models and simulations into behavioral insights and smart controls	Effective energy-saving solutions engaging human into energy savings behaviors	OB Engaging

2. Introduction – forewords.

In 2015, the building sector was responsible for 41% of the total energy consumption in Europe (IEA 2015) – 27% for residential buildings and 14% for commercial buildings – and in the United States (DOE 2015) – 22% for residential buildings and 19% for commercial buildings. In 2010, the energy consumption and CO₂ emissions of China's construction sector surpassed the United States level, emerging as the largest consumer of energy in the world (IEA 2015). The energy crisis, diminishing natural resources and global warming are driving developed countries to conserve energy in the building sector.

Energy conservation in buildings emerges as a paramount challenge to meet climate change mitigation targets. Moreover, it represents a key opportunity for technology developers, researchers, and policymakers to introduce innovative products, practices and energy efficiency standards. Governments worldwide are making setting aggressive goals to accelerate the uptake of energy-efficiency technologies and practices in buildings and to deliver high performing buildings.

However, at the current time, even designed high performing buildings are not performing as design.

2.1 The problem statement

Energy conservation in buildings has been widely recognized as a double challenge: partly technical, partly human-centered. A study (Turner & Frankel 2008) comparing the simulated designed energy consumption against the measured energy use of a group of 62 LEED (Leadership in Energy and Environmental Design) certified buildings in the U.S., showed a significant error (root mean square error of 18%) in energy consumption prediction. Results emerged scattered – Figure 1 (Turner & Frankel 2008) – indicating some buildings performed better than projected, with measured Energy Use Intensity (EUI) below the dotted line (perfect fit of measured and designed EUI), while approximately an equivalent total of buildings consumed more than expected.

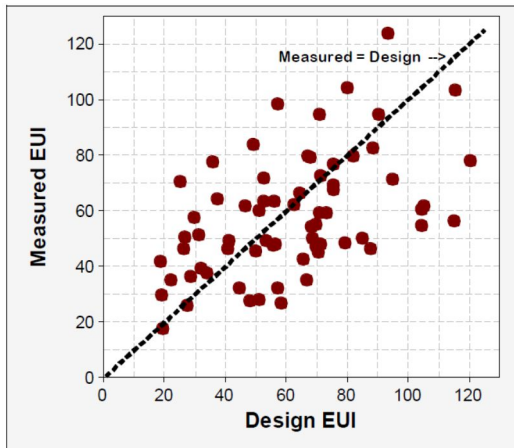


Figure 1. Measured versus Design EUIs. All EUIs in kBtu/SF (Turner & Frankel 2008)

For low energy buildings, which use passive designs and relies more consistently on occupant interactions with building systems and envelope to control indoor environmental quality, this prediction error emerged even larger. Researchers (Turner & Frankel 2008) justified this trend highlighting that “as technical performance standards ratchet tighter, behavioral factors gain relative importance”. This means high performing, low carbon, and passive buildings have the abundant potential to reduce energy use and to increase occupant’s comfort, satisfaction, and productivity – only if “operated as designed.” In other words, as technical barriers to energy efficiency in buildings are surmounted, a pivotal role is played by the human ability to control comfort and energy requirements in indoor spaces (Seyfang 2010).

A recent study (Day & Gunderson 2015) concluded that the probability of achieving the actual performance of high performing building is a factor of the occupant’s knowledge required to operate passive design systems and high-efficiency technology, as well as occupant’s expectation on comfort and environmental satisfaction (Deuble and de Dear 2012). A correlated research (de Korte et al. 2015) confirmed allowing occupants to directly control the indoor environmental condition of their indoor spaces without any provided information on the drawbacks of their action, can lead to even increasing energy consumption. What emerges is that uninformed or unintentional interaction with building envelope and control systems in order to restore a comfort condition within the indoor environments might have a negative impact on the predicted high-energy performance (Tanner & Henze 2013).

The phenomena of the ‘credibility gap’ of building energy efficiency were first introduced (Bordass et al. 2004) referring to the loss of reliability of building energy simulation and prediction when “design expectations of energy efficiency and actual building consumption outcomes differ substantially”. Authors advocated that credibility gaps arise not because occupants carry out ‘wrong’ actions, but because the assumptions made in the design phase are not enough informed by what happens during the real operation of buildings. Large discrepancies between measured and designed energy consumption in buildings are well recognized by ASHRAE 90.1 Standard, an international benchmark for building energy codes and standard. Credibility gap leads to the conclusion that energy efficiency is not merely a technology aspect, but requires the consideration of actual behavioral and operational aspects of building occupant energy-related behaviors. A

lack of longitudinal and real-time information on the actual occupants' energy-related behavior, preferences and drivers harvest the energy prediction accuracy. Moreover, it precludes the realization of comfort objectives and bounds the savings potential of energy efficiency measures.

The human decision-making process emerged driven by a vast array of features, called "drivers of behavior" (Fabi, Andersen, S. Corgnati, et al. 2012). Annex 53 (IEA EBC Annex 53, 2013) established a significant improvement in quantifying the primary driving factors influencing various types of human interactions with buildings and control systems (Wei et al. 2014). The driving forces reviewed from the different experiences were ordered accordingly six main categories and were organized as depending on external (building and building equipment properties, physical indoor and outdoor environment, time) and internal (biological, psychological, social) parameters. However, one limitation of this study is the application of such knowledge to the residential sector alone. In the residential sector, physical, social and cultural factors, which stimulate and/or coerce energy-related behaviors, such as age, gender, social class, income, geographical position and political differences must be taken into account (Fell & Chiu 2014, Han et al. 2013, Kavousian et al. 2013).

Differently in office buildings, it is necessary to achieve a deeper understanding of the motivation structure within the complexity of different social groups driving behavior in working environment (Delmas et al. 2013).

Moreover, when scaling up solutions from the building level to the urban scale, the micro-level factors influencing individual households' behavior need to be integrated to some mesolevel determinants related to the interaction of social factors and group behaviors, as well as to the macro-level factors coming into play at the community or national level.

2.2 The research big picture

An introduction section is established to frame the big picture of the occupant behavior research, regarding **what, why, who, when** and **how** the research arena is currently referring and dealing with the topic of occupant behavior in buildings.

- *What are occupant behaviors that have an influence on building energy performance?*

One first attempt in defining a common scientific agenda for the energy-related occupant behavior research has been completed between 2008 and 2013 by the International Energy Agency in the Buildings and Communities Program (IEA EBC, 2013), promoting a special taskforce on 'Occupant behavior and Modeling' in the 'Annex 53: Total Energy Use in Buildings: Analysis & Evaluation Methods'. Annex 53 Program firstly demarcated what is meant by **energy-related occupant behavior**. The term has been uniquely defined as "*observable actions or reactions of a person in response to external or internal stimuli, or respectively actions or reactions of a person to adapt to ambient environmental conditions such as temperature, indoor air quality or sunlight*" (IEA EBC Annex 53, 2013).

Accordingly, this dissertation refers alternatively to human or occupant behavior (OB) with respect to this broadly recognized meaning, taking into account actions and activities people perform in buildings to provide themselves with good indoor environmental quality (IEQ) (thermal, visual, acoustic comfort, indoor air quality, etc.).

Occupant behaviors can be split up into two distinct operations:

- 1) *adaptive actions* (Dear et al. 1998);
- 2) *non-adaptive actions* (O'Brien & H. Burak Gunay 2014).

The underlying principle for these *adaptive* behaviors (Dear et al. 1998) is the Humphrey's principles (Nicol & Humphreys 2002). It states that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort".

Hinging on this first category, occupants either:

- a) "adapt their environment to their needs" – e.g. opening/closing windows, lowering blinds, adjusting thermostats, turning on/off lighting, and/or
- b) "adapt themselves to their environment" – e.g. adjusting clothing, moving through spaces to avoid glare.

The second category refers to *non-adaptive* actions: occupant presence and operation of plug-in office equipment. Other types of non-adaptive actions are also included (Hong et al. 2015), such as reporting discomfort to a building manager, or choosing the possibility for inaction, when the occupant decides to do nothing but to suffer the discomfort. The occupant estimating the effort to mediate discomfort as too high could cause this. In other cases, the occupant has no access to adjustable systems. In addition, inaction can be an aware choice of the occupant consciously accepting more "forgiving" indoor environmental conditions. In this view, energy attitudes and social pressure drive inaction (Healey 2013). Similarly, an occupant might voluntarily modify his/her inclination to perform an action, which might alleviate his/her personal discomfort, due to the presence of other occupants who would be affected by the action (Anderson et al. 2014; Jain et al. 2013).

All these energy-related occupant behaviors become increasingly important in the determination of the indoor environment and building energy consumption (Nicol & Humphreys 2002). Simply, adaptive and non-adaptive energy-related occupant behaviors refer to those human actions and human-building interactions leading to changes in building energy performance in terms of alterations in internal heat gains, comfort demand, and operation of energy systems, hence influencing building energy and environmental performance.

Comprehensively, energy-related occupant behaviors include:

- (1) interaction with building systems and components, e.g. opening/closing windows, switching/dimming lights, pulling up/down shades, adjusting thermostat settings, turning on/off HVAC systems, and usage of plug loads (i.e. personal fans, heaters, domestic appliances, etc.);
- (2) presence and movement;
- (3) clothing adjustments;
- (4) providing comfort/discomfort feedbacks;
- (5) conscious inaction.

- *How to frame an international research agenda concerning occupant behavior in buildings?*

Occupant behavior has been recognized playing a major role in building performance. It is nowadays established as one of the driving factors of the observed discrepancy between simulated and actual building energy use. Despite years of dedicated empirical, monitoring, modeling and simulation studies and more than 400 articles published in top edge international journals in the field of building energy (Building and Environment, Energy and Buildings, Building Performance Simulation, and Building Simulation, etc.) since the 70', the occupant behavior phenomenon is not well understood. Causes of such unabridged gap need to be perused in the intrinsic complexity and multi-disciplinary nature of human behavior, lack or poor quality energy-related behavioral data, and the widespread application of over-simplified methods or tools to represent occupant interaction with building control system and components in building energy simulation. It is clear then, some questions are still open among the research community and a margin of improvement is pursued to improve the human integration in the loop of building energy efficiency.

To support this unabridged gap, as a further step of Annex 53 activities and outcomes, in 2013 the IEA EBC invested new resources to support the Annex 66 "Definition and Simulation of Occupant Behavior in Buildings" up 2017. Through involvement in international projects such as IEA Annex 53 and Annex 66, dedicated research efforts have been made by this Ph.D. study to understand occupants' interactions with building systems and to reduce their energy use in residential and commercial buildings over the entire building life cycle.

In this context, this Ph.D. dissertation aims to include theoretical insights supporting the international research community to frame an innovative multidisciplinary research agenda concerning occupant behavior in buildings.

- *Why understanding occupant behavior is crucial for low energy buildings?*

A number of studies demonstrate the pivotal role of occupant behavior in determining huge variability in terms of comfort settings and energy use driven by control systems, building component and appliances usage in building (Lin & Hong 2013; Jian et al. 2015; Majcen et al. 2013; Tanimoto et al. 2008; Turner & Frankel 2008). Such trend is established both in office and residential buildings. Moreover, this human factor in building energy consumption is documented as an international phenomenon having no geographical bounds.

In the context of commercial and office buildings, the 'dark side of occupant behavior on building energy use' was demonstrated (Masoso & Grobler 2010). The work showed energy was wasted in office buildings because of inefficiencies in controlling indoor environmental quality at the zone level, as well as because of recursive behavioral habits i.e. leaving lights and equipment on at the end of the day. A study (Chang and Hong 2014) demonstrated – by using measured lighting-switch data as a proxy of occupant occupancy – occupants with "wasteful" work-style may consume up to 90% more energy than standard users while "austerity" work-style occupants used half of the energy of the "standard" occupants.

Equally at the household level, energy consumption among individual dwellings has been shown to fluctuate largely, presumably due to occupants' behavior (Chen & Taylor 2013). A study (Andersen et al. 2009) demonstrated that energy consumption of 35 apartments located in Denmark – having almost identical characteristics in terms of orientation, building systems and building envelope composition – may vary up to a factor of 3. A similar factor of variation is

supported for the US residential building sector (Parker et al. 2012). This study is based on the comparison of the total energy use of 10 homes in Florida (US), having the same floor area, located on the same street and built in the same year and having comparable system efficiency. This variation emerged to be even larger (up to a factor of 10.6) when comparing the space heating energy use alone. In an equivalent trend, a study conducted in China (Zhou et al. 2014; Center 2012) showed a variation up to a factor of 10 of the measured residential summer air-conditioning electricity consumption, across apartments having similar dimensions and located within the same block of buildings. For low energy buildings, relying on passive design features (e.g. natural ventilation and use of daylight) and proactive interaction between occupants and building systems, the prediction error appeared even larger (Parker et al. 2012).

- *When can the occupant behavior research be applied to improve the building life cycle?*

Integrating occupant behavior is critical to achieving zero-net-energy buildings during the whole life cycle. Studies in the field involve the consideration of occupant behavior in building energy use during the design, operation and retrofit of buildings.

- Building simulation tools, including more advanced behavioral model, have been demonstrated to enhance the **design** accuracy of building energy performance, bridging the gap between predicted and measured energy consumption and comfort level.
- Including humans in the loop of sensing and control of building can improve **operation and management** of buildings, demonstrating saving in the range of 4-5% of energy operating costs in commercial buildings alone.
- Also, a better understanding of the human factor on building energy use can support the definition of efficient and targeted **retrofit** strategies. In this context, including evaluations on technology adoption and penetration based on socio-economic behavioral variables in current energy retrofit scenarios can support the uptake of robust energy efficiency measures.

Moreover, the systematic interconnection of the human- building interaction is paramount at different scales.

The building system and occupant behavior are observed at the both in residential and commercial buildings. Data are gathered, analyzed, modeled, standardized and simulated from the zone to the building level, up to the district scale.

With respect to occupant behavior, studies focus on individual, group and collective behaviors.

The connection of these scales and focuses of research is not linear. Rather, a trans-scalar approach must be adopted to explore solutions able to overcome actual limitations and shortcomings in state-of-the-art research.

- *Who are the stakeholders involved in the occupant behavior research?*

Occupant behavior research focuses on building **occupants** specifically. However, outcomes of the research in the field are intended to provide benefits to different stakeholders of the building industry, acting their role in different stages of the building lifecycle. Involved subjects include **building operators** and **managers, designers** (architects and engineers), **practitioners, policy** and **institutional decision makers**.

On the one hand, these stakeholders should improve their professional expertise in the field of building energy efficiency techniques and measures. On the other hand, they should equally seek solutions for integrating the human factor during the design, operation and retrofit stage of building performance assessment– namely energy consumption and IEQ requirements.

Also, the knowledge discovered by advanced behavioral data analytics aims to support *energy and urban planners* to the development of tailored energy policies (i.e. technology driven retrofit measures) and more resilient energy urban planning tools, targeting energy efficiency in building.

2.3 The state-of-the-art research limitations

This dissertation focuses on the actual gaps of the state of the art research on the topic of occupant behavior in buildings, in order to proffer general proposals regarding how to overcome these deficits.

The major themes include advancements in sensing, analytical and modeling methods, simulation applications in building energy software, as well as the application of behavior theories, user engagement techniques, which provide insights into energy-related behavior impact and savings potential, from the residential and commercial building level, up to the urban scale. In order to deliver original research outcomes, the state of the art in the field must be scrutinized with rigor and critical perspective. In the following section, the key research limitations have been summarized, as pertaining to five paramount fields of investigation of the energy-related behavior phenomena.

2.3.1 *Oversimplified or ignoring actual human-building interaction*

The core idea hinging on the human-building interaction concept is that “*buildings don't use energy, people do*” (Janda 2011). This implies energy is not directly used by building system and components, but from the occupants of the buildings. However, occupants are not “perfect machines” nor “passive receivers” of the indoor environment they live or work in. Instead, building occupants actively interact with their indoor environments in seeking for a personally comfortable condition (Langevin et al. 2015). The underlying principle for this phenomenon is called the Humphrey's principles (Nicol & Humphreys 2002). Authors advocated that any change in indoor environmental condition that produces a reduction in thermal, visual, indoor air quality comfort levels, drives people to actively bring about (or restore) their personal comfort conditions.

Moreover, human behavior is stochastic by nature and comes from the consequences of stimuli – also called drivers of behavior – but this relationship is not linear (Hong, D'Oca, et al. 2015). Individual subjects might react differently based on similar environmental conditions, meaning there is no standardize approach or solution to replicate the decision-making process leading uncomfortable occupants to actively interact with building components (O'Brien and Gunay 2014).

The concept of effectiveness of human interaction with the building control systems implies that occupants are allowed to use controls, understand how to use them, but it also has implications for the provision of the building system of tangible feedbacks to the users to each potential control action (Dennis et al. 1990). Accordingly, current innovations in sensing, control, and visualization technologies are leading contemporary smart building management energy systems to monitor human preferences, habits, and patterns of interaction with building technologies.

Such innovative building management technologies are based on the implication of humans as perceptual sensors and controllers of the energy and comfort systems. However, despite the great potential of building energy savings, solutions of such are still little employed on the large scale.

The key problem with contemporary forms of environmental monitoring and control systems is that the flow of information within the building-human-data systems is poorly understood, compared to the flows of energy. To allow this smartly optimized control, rigorous observation techniques of the human-building interaction needs to be employed. Behavior monitoring through active and passive sensing of the human-building interaction will establish the ground foundation for any valid further development research and technology innovation in this field. In this view, **sensing building and human data emerge as the new trend in building energy efficiency.**

2.3.2 Deficiency of effective analytic techniques providing knowledge

With the growing usage and technology development of Internet of Thing (IoT) connected devices, the cutting costs of building and occupancy parameters, real-time smart metering systems and the increasing trend in self-monitoring, large amounts of data are available in the building sector. Currently, granular real-time measurements of the occupant presence, movement and interaction with system controls (thermostats, lighting) and building envelope action (windows, shades) are largely streamed. Sensor networks enable multidisciplinary and integrated layers of big data source collection, providing reliable information on occupancy recognition and scheduling, in addition to building performance and operation. **However, how to translate building and human information into useful knowledge driving energy efficiency in buildings is still an open question.**

Statistical analysis techniques are extensively applied to discover associations and relationships among the various factors influencing building energy performance and occupant behavior in buildings. Different suitable user behavioral models were defined by means of statistical analysis, for which an extensive review of these studies has been conducted in the context of Annex 53 (IEA EBCP 2013). The strength of this methodology is their simplicity and widespread familiarity. Some high-level trends in occupant behavior can be highlighted having statistical relevance, i.e. occupants opening the window when arriving the office or when driven by comfort requirements. However, no matter the accuracy of the statistical model, such discovered correlations are contingent to a specific observation study. Furthermore, it is currently undefined how to apply stochastic models of occupant behavior in open-plan spaces, or shared offices, where multiple occupants having variable schedules and behaviors must be characterized. Further, how to represent the social and contextual interferences of group behavior and order of behavioral adaptations with respect to energy use in buildings is an explored field. This implies a description of individual behavior, as standardized repetition of actions performed by a group of heterogeneous subjects, may not lead to truthful occupant behavior representation.

In addition, associations among variables found to have little statistical correlation between isolated occupant behaviors or small data set may lead to the understanding of more general patterns of behavior in a large data set, helping direct efficiency measures at the district and urban scale. This implies statistical relevant information on energy-related behavior can be supplementary to discovered behavioral patterns, overcoming the lack of personalization of statistical methods (Han J et al 2007).

Data mining techniques lead the way to automatically analyzing huge amounts of data and patterns extraction from big databases, as demonstrated by large diffusion into research fields such as marketing, medicine, biology, engineering, medicine, and social sciences. Application of data mining techniques to building energy consumption and operational data is still in an elementary phase. However, this approach is favorably seen (Yu et al) as a prominent field of discovery to provide insights into energy patterns related to the occupant behavior, facilitating evaluation of building saving potential by improving users' energy profiles as well as driving building energy policy formulation.

2.3.3 Lack of common agreement on modeling and simulation approaches

Over the last 30 years, behavioral interactions with building and systems, based on measurements of real occupant behaviors, started to be virtualized in building energy models by means stochastic models reflecting human's variability (Annex 53, EBCP 2013) Such stochastic occupant behavior models typically refer to implicit or explicit models (Hong et al. 2015). Implicit models interpret variation in states of the building component as a proxy for occupant behavior. More accurately, explicit models account for the state-transition of a building component or a variable of the indoor environment as the event of behavior.

Approaches for implementing such data-driven behavioral models emerged scattered among published research in literature (Gunay et al. 2015). In the reviewed literature, four different adaptive behavior model forms were found: (1) schedules, (2) Bernoulli models, (3) discrete time Markov models, and (4) discrete event Markov models. The formalisms classify whether the models predict the occupants' adaptive actions or the state of the building components with which occupants interact. The first two model forms were defined as implicit, and the last two were defined as explicit models (Hong et al. 2015). Implicit models predict the states of the building components with which occupants frequently interact, whereas the explicit models directly predict occupants' interactions with the construction components. In other words, implicit models focus on predicting the state of some building component as a proxy for behavior (i.e. a window is open because an occupant opened it), while explicit models directly predict behavior (i.e. the action of window opening).

However, the adoption of diverse methodologies is not necessarily a matter of complexity. More significantly, it entails on the relative significance modelers are attributing in their models to some predictor variable driving occupants for intervening upon their indoor environment (Parys et al., 2011)

Behavioral models started to be implemented in the most widespread simulation tools, such as Energy Plus, IDA ICE, ESP-r, DeST, TRNSYS, DOE-2, in order to improve the outcome of actual simulation of building energy consumption. However, many of the implemented behavioral models are not available for a straightforward application in building energy models (Stoppel and Leite 2014). The non-trivial environment of common simulation engines, having unfriendly interfaces and requiring programming knowledge and specific code validation procedures to incorporate behavioral custom component models exacerbates this shortcoming (Hong et al, 2016).

Further, when behavioral model embedding is allowed via source-code alteration, peculiar data syntax and structure of each of the simulation engines do not permit flexibility or standardized way to achieve transferability of behavioral models between building simulation tools. This means, in practice, that behavioral models implemented into one software tool, cannot be reused for similar purposed in different simulation environments. Without a common agreement on a technical structure for describing and implementing energy-related models of occupant behavior in building simulation tools, simulation results become difficult to compare, impeding the research community to attain general validity of occupant behavior simulation outcomes (Hong et al, 2016).

2.3.4 Inadequate behavioral inputs in building energy simulation

Human-building interaction has the peculiar characteristic of representing a complex information system whose inputs cannot be treated as predetermined controls. A further important consequence of this adaptive interaction entails a probabilistic treatment of the occupant information variables, which needs to be included in building energy models. A present challenge deals with the oversimplification of existing occupant behavior inputs in dynamic simulation models, leading to a “credibility gap” of building energy performance (Bordass et al. 2004). Since the 70’s, occupants have been modeled in building performance simulations as parameters to the plant operation (Willey 1988). Regrettably, little change in such deterministic modeling tendency emerges even in current practices. The actual stochastic nature of the occupant is still typically condensed into *deterministic schedules* ignoring the diversity and interdependency of various behavioral and seemingly stochastic actions.

The term *deterministic* entails the concept the likelihood of an occupant to perform a certain action with respect to the interaction with building components, envelope, and plant system is modeled by average values of some predictor variable or fixed input recommended by norms, codes and standards.

The term *schedule* refers to a standardized representation of occupant-related factors over time, which is typically used to design occupancy when actual occupant behavior is unknown. Schedules are daily profiles, taking different forms for weekend and weekdays. They are composed of hourly values, each of which corresponds to a fraction of the occupancy or the occupant behavior load. Often building occupancy schedules are grounded on general conventions relying on standards or energy codes.

As an example, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2004 provides standardized occupancy diversity factors for building types. The main advantage of using deterministic inputs of occupant behavior is they ease of use and application to a broad range of adaptive behavior and building types. However, one of the drawbacks is their intrinsic weakness in capturing the diversity of individual behavior. This randomness can have significant implications for building energy control and demand. Such oversimplified assumptions on occupant behavior are creating inconsistencies between simulated and actual building energy performance (Figure 1)



Figure 1. Typical Monday-Friday Schedule representing diversity profiles Standard 90.1-2004 compared to stochastic occupancy schedules generated via a building energy simulation tool (occupancysimulator.lbl.gov)

2.3.5 Lack of effective solutions and insights to leverage energy saving

Humans can perceive comfort conditions, but are not physiologically prepared to sense energy consumption (Reay and Wright 2013). Accordingly, occupants are essentially unconscious of the energy drawbacks of the control actions they undertake in order to restore a comfort condition in the indoor environments. Results of a European Environmental Agency report (Griffiths 2012) underlined that the energy saving potential for improving energy consumption patterns in homes ranges from 5% to 20%, based on the type of intervention, and is on the average among 15%.

Leveraging on improving occupant behavior in the commercial sector, studies demonstrated a 30% reduction is achievable (Lin & Hong 2013). Such low cost and non-technological measures can be compared to structured investments for improving building energy efficiency, requiring higher investment costs, and more intensive deployment plans. Nonetheless, achieving such behavior energy-reduction targets is still a little-accomplished task. This is because - despite statistics and model predictions - people tend to respond to unpredictable ways when it comes to energy-related behavior in indoor environments such as homes and working spaces. Household consumers are not merely driven by financial incentives to save energy in their homes, because of their requirements for comforts and accomplishments of material needs and duties. Also in office buildings, it is necessary to achieve a deeper understanding of the motivation structure within the complexity of different social groups driving behavior in working environment.

However, occupant behavior in offices cannot be accustomed to some 'typical' pattern, because of intrinsic desires, attitudes and intentions with respect to the collective responsibility in energy savings. Energy users, technicians, and practitioners seem to have gained awareness of the benefit and need for more sustainable energy-related behavior in buildings, on the path towards a changing consumer paradigm. However, despite this growing public concerns, yet a lack of adequate knowledge emerged on how occupants can practically save energy in buildings and how technicians, researchers and policy makers can effectively drive the uptake of behavioral change practices into the building science. Together with the emerging behavioral studies of building physics, ICT, and the upward human behavior modeling know-how, a "multidimensional knowledge" is foreseen as a promising field to draw critical expertise on the behavioral energy use phenomena in buildings.

3. Methodology

“If I have seen further, it is by standing on the shoulders of giants.”
 - Isaac Newton

This Ph.D. dissertation is structured as an assemblage of research outcomes aiming to illuminate innovative solutions and insights to bridge the limitations of current research on the topic of energy-related behavior in buildings.

A methodological approach is adopted to give answers to a collection of unresolved questions, as *fil rouge* connecting the three years of research. The proposed research methodology has foundation on the core concept that the issue of the human behavior in building energy use is a stochastic and highly complex problem, which cannot be solved by one discipline alone. This is the typical approach of current researchers in the field.

Progressing past that, this research integrates occupant behavior in a multidisciplinary methodology that combines insights from the technical, analytical and social dimension. This is achieved by combining building physics (occupant behavior simulation in building energy models) and data mining analytics (occupant modeling and profiling) with behavioral theories (occupant engagement) to provide multidisciplinary innovative insights on human-centered energy efficiency in buildings.

Accordingly, the three-year research conducted under the framework of this dissertation has been steered by a multidimensional systematic approach, which envisions a triangulated two-way communication exchange between the building, data, and human systems. (Figure 1).

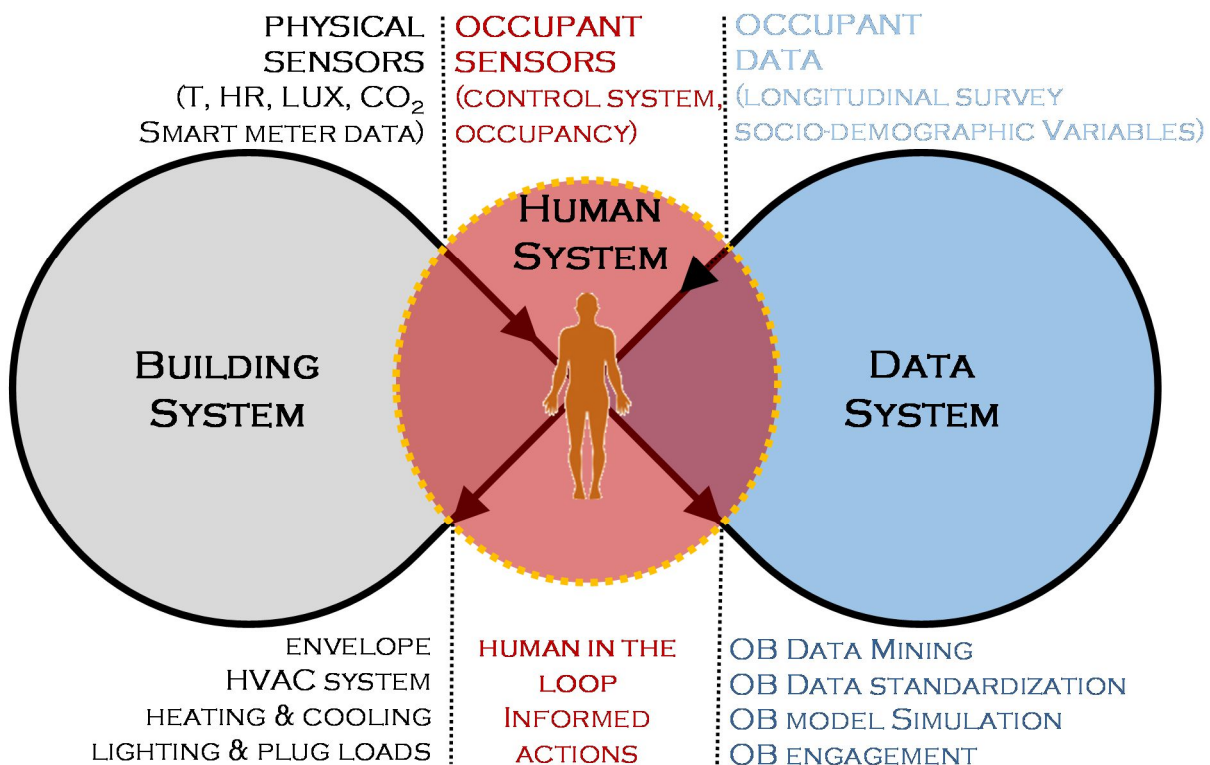


Figure 1. Schematic Overview of the building-data-human in the loop approach

- The **Building system** refers to elements for heating and cooling, the HVAC system, the electric system (lighting and plug loads), and building envelope components with whom building occupants might interact (windows, shades, blinds, etc.). Physical sensors monitoring indoor environmental parameters, such as temperature, relative humidity, illuminance level, and carbon dioxide concentration and smart meters (i.e. collecting plug loads and electricity data) achieve the observation of such system.
- The **Human system** includes the notion of Human-in-the-Loop (HIL), as technology innovation enables occupants to become both passive sensors and active controllers of the IEQ. Occupant receiving feedbacks on comfort levels and energy intensity in indoor spaces will perform actions that are more “informed” and aware. The Human system refers to the occupant presence, movement in and within the indoor spaces, and to the occupant interaction with the building control system. The observation of this system is attained via occupancy and motion sensors, by monitoring the human interaction with the building envelope components, such as window, shades, and blind state.
- The **Data System** transforms the data information collected from the building and human systems into useful knowledge to drive energy efficiency in buildings, during different stages of the building life cycle: design, operation, management, and retrofit. The data system operates via dynamic building energy simulation models (such as IDA ICE, Energy Plus), analytic (statistical analysis and data mining techniques) and visualization platforms to deliver guidance and feedback to building designer, managers, operators, and occupants.

Characteristics of the research methodological approach are summarized in Table 1.

Table 1. Summary of the HIL multidimensional systematic approach

System	Building	Data	Human
Dimension	Technical	Analytic	Social
Field	Building Science	Data Science	Behavioral Science
Area Of Research	Building Physics, Architectural Engineering	Data Analytics ICT	Behavioral Theories, Psychology, Sociology
Expertise	Building Energy Simulation Thermal Comfort and IEQ	Data Mining, Statistical Modeling	User engagement, Persuasive communication
Scale	Residential, Commercial Building	Zone, Building, Block Of Building Level	Individual, Group, Collective Behavior
Improvements	Building Energy Models	Building-occupant controls	Occupant Behaviors

The developed methodology embraces research expertise from different fields of building science (building physics and architectural engineering), data science (data analytics and ICT), and behavioral science (behavioral theories, as well as human psychology and sociology insights).

Without the presumption of fully covering the broad knowledge of these grounds of sciences, research has been conducted with consistency driven by advanced education in the diverse areas of research. This has been achieved by formal academic expertise in the field of architectural engineering, thermal comfort, and IEQ, advanced studies of data mining techniques and statistics modeling methods, as well as meticulous literature reviews of behavioral theories, user engagement and persuasive communication techniques. The innovative methodology is integrated into a three-step Human in the Loop (HIL) research approach, as illustrated schematically in Figure 2.

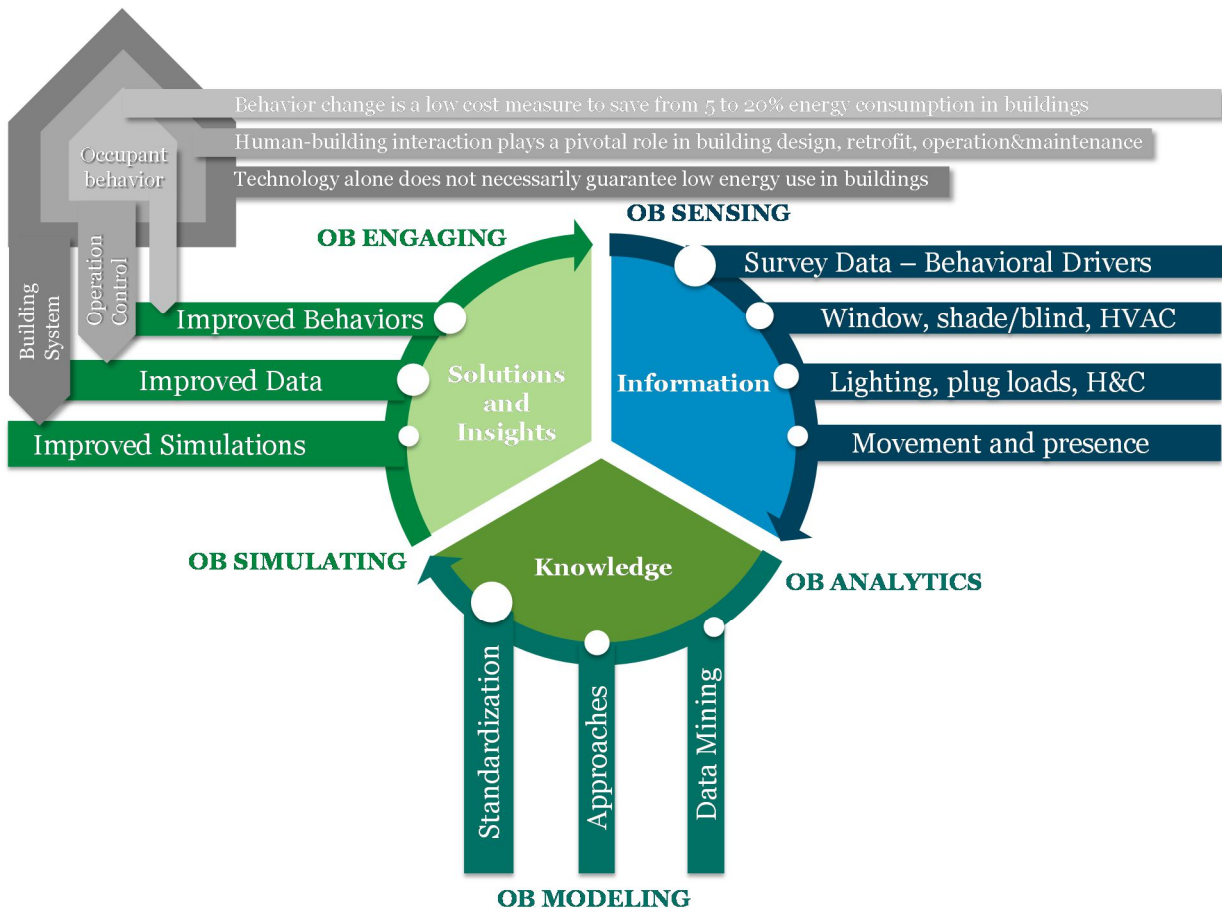


Figure 2. Schematic Overview of the dissertation research approach

The methodological section of this dissertation focuses on applying multidisciplinary methodologies to fill gaps in information, knowledge, solutions and insights on energy-related behavior in buildings.

- Firstly, **information** on the building-human interaction is provided via observation studies.
- Based on sensed data, **knowledge** on the human factor in building energy use is discovered through energy-related behavior data analytics and model standardization.
- Finally, **solutions and insights** are provided in order to improve the accuracy of building simulation outcomes, enhance the informative power of monitored human-building data streams and enable energy efficient occupant behavior in buildings.

Compared to current state of the art alternatives illustrated in the introduction section, the methodological principles of this dissertation aim to overcome shortcomings, limitations, and challenges by integrating occupant behavior in buildings with an innovative approach in terms of occupant behavior:

- i. Sensing
- ii. Analytics
- iii. Modeling
- iv. Simulation
- v. Engaging

Correspondingly, what the scope of this thesis research on occupant behavior is to raise some unresolved research questions to be addressed, as follows:

- i. How to study occupant behavior based on facts and not hypotheses?
- ii. How to translate building and human information into useful knowledge?
- iii. Which are the strengths, shortcomings, and needs of the actual modeling and simulation methodologies?
- iv. Is there sufficient benefit in quantifying OB in building energy simulations?
- v. How to engage effectively the human operator into optimized control formulation in buildings?

A flow chart systematizing the dissertation methodological approach to the research is provided in the following, and summarized in Figure 4.

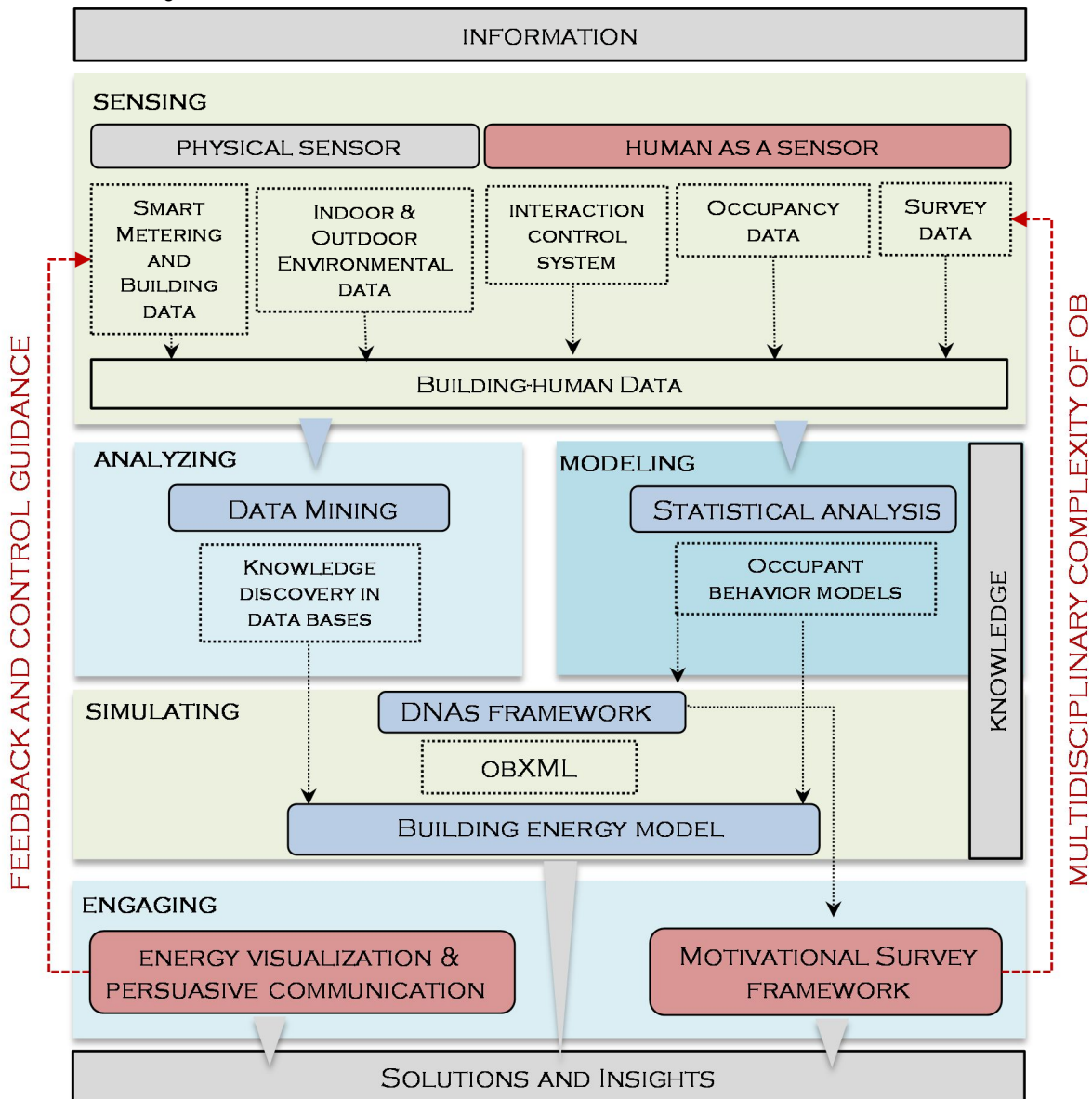


Figure 4. Schematic Overview of the methodological research approach

Adequate **sensing** procedures of actual energy use and behaviors in building (monitoring techniques, surveys, etc.) establish the ground foundation of robust building-human data sets [Paper 1]. However, how to gain information on occupant behavior based on facts and not hypothesis is still an open question. Questionnaire survey emerged as optimal tools for discovery of a new layer of social, contextual and group interaction constructs related to driving forces and individual motivations.

Building and human information need to be translated into useful knowledge driving energy efficiency in buildings. Improved data **analytics** methods (data mining, statistical analysis) can lead to the development of advanced occupant behavioral models, patterns and profiles [Paper 2, 3, 4].

The strengths, shortcomings of the state-of-the-art **modeling** approaches are identified, illustrated, and discussed [Paper 5]. To this end, a critical review of the existing occupant model forms from the literature has been conducted. Among the simulation community, little agreement and understating on how to implement such behavioral models into current BEM **simulation** tools has been reached.

Accordingly, behavioral model validity and transferability are sought by means the establishment of a common standardized framework among the international community, unfolding the cognitive dimension of occupant-human interaction through Drivers, Needs, Actions and Systems (DNAs) [Paper 6].

Grounded on the DNAs framework, a syntax (XML language) for representing a comprehensive library (obXML) of energy-related occupant behavior in buildings is established [Paper 7].

When implemented into current building simulation tools, validated behavioral models are supposed to develop energy prediction closer to reality [Paper 8, 9].

Finally, the knowledge gained must be employed to provide solutions and insights on how to **engage** effectively the human operator into optimized control formulation in buildings. Leveraging on improved communication on energy usage and IEQ between the building-data-human systems, behavioral science insights are applied to engaging energy-aware behaviors in residential buildings [Paper 10].

However, engaging office users into comfort-adaptive and energy-saving behavior is grounded on diverse multidisciplinary drivers. A survey research framework is hence developed to provide quantitative descriptions on the collective and social motivations within the complexity of different social groups in working environment, under different geographical context, culture and norms [Paper 11].

Further advancements of the presented study are the operative rollout of an extensive survey questionnaire campaign in different geographical locations, among the international research community embracing the IEA EBC Annex 66 on “Definition and Simulation of Occupant Behavior in Buildings”.

The final aim of this study – in a broader perspective – is to provide a standardized multidisciplinary methodological approach to enhance the state of the art on information, knowledge, and insights on energy-efficient occupant behavior in the building sector.

4. Results

“Science, my boy, is made up of mistakes, but they are mistakes which it is useful to make, because they lead little by little to the truth.”

– Jules Verne, *Journey to the Center of the Earth*

A result section presents and discusses investigation approaches supported by a collection of peer-reviewed research outcomes.

Accordingly, this dissertation advises innovative research to meet the actual international community enhancements in the field of:

1. *Sensing techniques of the multidimensional sphere of human-building interaction*
2. *Improving occupant behavior data analytics and Knowledge Discovery in Databases*
3. *Standardize occupant behavior modeling approaches and implementation in building simulation information systems,*
4. *Enriching outcomes of occupant behavior simulation in BEMs*
5. *Translating data, models and simulations into behavioral insights and solutions to engaging occupants into smart and energy-efficiency building-human interactions*

After introducing and critically analyzing the state of the art of studies in the field, and describing the methodological structure of the proposed research, this dissertation focused on providing and discussing occupant behavior innovative results outcomes in occupant behavior information gathering, knowledge discovery and solution and insights development, as described in the following (Table 1).

Table 1. Research outcomes of the dissertation methodological research approach. Occupant behavior research grounds on focus, related innovation fields, and connection with research outcomes.

OB Focus	Innovation	Topic of research	Research Outcomes
SENSING	Information	Critical review and guidelines for OB Sensing techniques	Paper 1
ANALYTICS	Knowledge	KDD of window opening in commercial building	Paper 2
		KDD of occupancy in commercial building	Paper 3
		KDD of socio-demographic variables in block of buildings	Paper 4
MODELING		OB modeling approaches	Paper 5
		DNAs Framework	Paper 6
		obXML schema	Paper 7
SIMULATING	Solutions and Insights	BEM Simulation residential building	Paper 8
		BEM Simulation commercial building	Paper 9
ENGAGING		User engagement in residential buildings	Paper 10
		OB Survey Framework in commercial buildings	Paper 11

1. Provide information on the building-human interaction via observation studies (sensing).

Paper 1

Review of the state of the art achievements and gaps of techniques and methodologies of observation of energy-related behaviors. Research focuses on *adaptive actions*: occupant changes that alter the environment to make it more comfortable (thermal, air quality, light, noise), including window-opening behavior, usage patterns of thermostat or air conditioning, and *non-adaptive actions*: operation of lighting and appliances and occupant presence and movement into indoor spaces

Transversal questionnaire survey emerged useful tools to gain information on general behavioral patterns and drivers and to find connections between human, social and local comfort parameters. Based on an extensive literature review (Belafi et al, 2016), gaps were identified and guidance was given for future survey studies. It was concluded that insights from social practice theories and techniques must be acquired to deploy robust and unbiased questionnaire results, which will enable to gain new and more comprehensive knowledge in the field and to compare energy-related occupant behavior in office buildings among different cultures, climates and countries.

2. Discover knowledge on the human factor on building energy use through energy-related behavior data analytics and model standardization.

Paper 2

In a first exploration study, a data mining framework based on the Knowledge Discovery in Database (KDD) is suggested as an improvement of the notion of behavioral patterns not only as merely statistical relevant clusters but also incorporating the driver-response conditioning dimension with typical window opening habits.

Paper 3

Secondly, a study applies the KDD data mining process to extrapolate information on occupancy schedule patterns from measured building big data streams.

Paper 4

When scaled up from the building level to the district and urban level, the description of the human factor in building energy use, needs to progress from the notion individual energy-related occupant behavior – in terms of interaction with control system and building envelope – up to the interpretation of those anthropic building-specific factors which affect the uptake and deployment of energy efficiency measures and standards. Accordingly, a third methodology based on the KDD was employed for discovering the leverage of socio-demographic variables influencing energy consumptions and penetration of packages of retrofit measures at the district level.

Paper 5

A critical review of the existing occupant-modeling concepts published in literature has been conducted as part of the Ph.D. studies. The objective of this paper was to identify, illustrate, and discuss the strengths and weaknesses of the state-of-the-art modeling approaches of occupant behavior. In the reviewed literature, four different adaptive behavior model forms were found: (1) schedules, (2) Bernoulli models, (3) discrete time Markov models, and (4) discrete event Markov models. The first two model forms were defined as implicit, and the last two were defined as explicit models. Implicit models interpret variation in states of the building component as a proxy for occupant behavior. More accurately, explicit models account for the state-transition of a building component or a variable of the indoor environment as the event of behavior. Examples of each model type predicting: a) the states of the building components and b) the event (state transitions) of the building components were developed upon two data sets from an academic office building in Ottawa, Canada and a government building in Hartberg, Austria. The critical analysis of existing modeling approaches and a discussion of empirical and simulation outcomes of the research lead to the conclusion that direct discrete-event models overcome a wide array of weaknesses emerged among the other modeling approaches.

Paper 6

The need for a standardized language to represent and communicate OB models in building energy simulation emerged. Without such a common agreement, simulation results become difficult to compare, impeding the research community to attain general validity of occupant behavior simulation outcomes.

Based on extensive reviews of more than 130 journal articles publishing energy-related behavioral models and studies, an ontology framework is designed to provide the research community with a distinctive systematic approach to describing the energy-related behavior phenomena in buildings, based on Driver, Need, Action and Systems (DNAs).

Paper 7

Based on the DNAs framework, a standardized eXtensible Markup Language (XML) schema is adopted to represent OB models (obXML) in building energy models. The obXML schema has the intrinsic flexibility to represent numerous, diverse and complex types of occupant behaviors in buildings, and it can also be expanded to incorporate new types of behaviors.

The implementation of the DNAs framework into the obXML schema is intended to facilitate the development of an organized syntax providing interoperability between occupant behavior models implemented into diverse building energy modeling programs.

3. Provide insights via dynamic building energy simulations applying behavioral models to improve the accuracy of energy building performance prediction.

Paper 8

A residential model implementing stochastic behavioral models for window opening and closing behavior and for usage of thermostats, also differentiating among active, medium and passive users, in order to leverage the variation in heating consumption at the dwelling level.

Paper 9

An office building energy model is implementing behavioral models for window opening behavior, usage of heating and fan systems as interaction with blinds, to test the robustness of different building envelope design and climate conditions with respect to the overall energy balance of the building.

Provide solutions to engage occupants in residential buildings towards energy-savings and enhancement of energy efficiency at the household level.

Paper 10

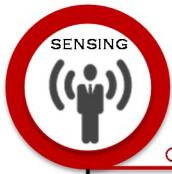
A pilot study was conducted in Italy to test the effectiveness of a smart monitoring system in reducing domestic electricity consumption by engaging householders towards energy-savings behaviors. The conducted study combined an energy visualization and feedback dashboard with a persuasive communication campaign providing tailored peer-compared information and advices for reducing energy usage.

Paper 11

Differently from the residential sector, when engaging occupant behavior in working environments, it is necessary to achieve a deeper understanding of the motivation structure within the complexity of different social groups driving behavior. Accordingly, rather than focusing on individual behaviors and influencing factors – predominantly relevant in the domestic sector – a motivational survey framework is developed to gain insights on collective and social conventions of energy-related behavior, shaped by geographical and climatic contexts, culture and norms.

Table 2. Summary of selected research outcomes and list of related publications.

Research Outcomes	Authors	Related Publications	Year of publication	Publication
Paper 1	T. Hong, S. D'Oca et al.	Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings.	2015	ENERGY AND BUILDING
Paper 2	S. D'Oca, T. Hong.	A data-mining approach to discover patterns of the window opening and closing behavior in offices.	2014	BUILDING AND ENVIRONMENT
Paper 3	S. D'Oca, T. Hong.	Occupancy schedules learning process through a data mining framework.	2015	ENERGY AND BUILDINGS
Paper 4	S. D'Oca, S.P. Corgnati, et al.	Testing Socio-Economic Demographic Variables on building energy consumption scenarios at the urban scale in Italy.	2015	Proceeding of ClimaMed 2015, France
Paper 5	S. D'Oca, et al.	A review of the occupant modeling approaches in offices with illustrative examples	2016, submitted	JOURNAL OF BUILDING PERFORMANCE SIMULATION
Paper 6	T. Hong, S. D'Oca, et al.	An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs Framework.	2015	BUILDING AND ENVIRONMENT
Paper 7	T. Hong, S. D'Oca et al.	An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAs framework using an XML schema.	2015	BUILDING AND ENVIRONMENT
Paper 8	S. D'Oca, S.P. Corgnati et al.	Effect of thermostat and window opening occupant behavior models on energy use in homes,	2014	BUILDING SIMULATION JOURNAL
Paper 9	S. D'Oca, S.P. Corgnati et al.	Insights into the variability of energy consumption due to adaptive occupant behaviors in offices: a simulation study	2016, submitted	BUILDING SIMULATION JOURNAL
Paper 10	S. D'Oca, S.P. Corgnati et al.	Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings,	2014	ENERGY RESEARCH & SOCIAL SCIENCE
Paper 11	S. D'Oca, S.P. Corgnati et al.	Introduction to an occupant behavior motivation survey framework.	2016	Proceedings of Clima2016, Aalborg Denmark



OVERSIMPLIFIED OR IGNORED ADAPTIVE AND NON-ADAPTIVE OB BUILDING OPERATION PROCESS

HOW TO STUDY OB BASED ON FACTS AND NOT HYPOTHESIS?

PAPER 1

T. Hong, **S. D'Oca** et al.

Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings.
ENERGY AND BUILDINGS – 2015

4.1 OB Sensing

“Measurement is the first step that leads to control and eventually to improvement. If you can’t measure something, you can’t understand it. If you can’t understand it, you can’t control it. If you can’t control it, you can’t improve it.”

– H. James Harrington

State of the art limit of research	Unabridged research questions	Innovations	Outcomes
Oversimplified or ignoring actual occupant behavior throughout the building operation process	How to study occupant behavior based on facts and not a hypothesis?	Sensing the multidimensional sphere of human-building interaction	Critical survey review and guidelines for OB monitoring and survey techniques

In discussing human behavior we refer to stochastic responses to trigger events. These responses are not random phenomena but occur following a determined tendency. The fundamental question in **how to observe such tendency**, in order to understand – and hence predict – the probability of a specific behavior to occur as a function of explanatory variables. Sensing building and human data is the new trend in building energy efficiency. Data-driven techniques to gather real-time remote measurement of occupants’ presence, movement, interaction with building technologies and usage of plug loads are rapidly expanding in both residential and commercial buildings. Behavior can be measured by indirect or direct sensing. Accordingly, measurements of energy-related behavior are generally collected by means physical sensors or by including human sensing (Figure 1).

Typically, indirect occupant behavior sensing includes measurements of the influencing variables driving behaviors, such as indoor environmental parameters (CO₂, Ta, RH, lux level, etc.) and outdoor environmental parameters (Tout, event of rain, etc.) as well as contextual parameters (time of the day, day of the week, geographical location) and state of control systems (window/open closed, thermostat turned on/off, blinds up/down). Physical sensors gather measurements of indoor and outdoor environmental data as well as smart metering (plug load, electricity) and building data (IEQ, energy loads). Including humans in the loop of sensing technology entails occupant direct “passive” sensing – i.e. occupancy sensors, monitoring interaction with control systems –, as well subjective measurements techniques involving humans as “active” sensors – i.e. asking directly occupant to self-report their interaction with building control system and building component, or by using survey techniques.

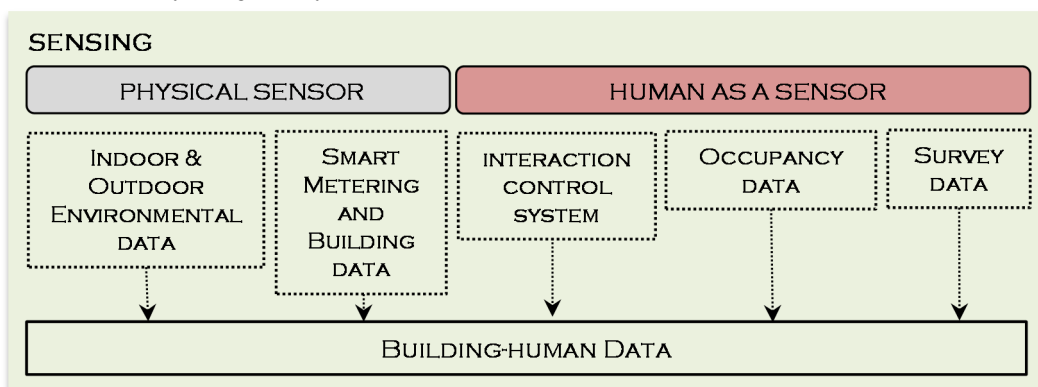


Figure 1. Schematic of the sensing methodological approach of occupant energy-related in buildings.

Paper 1

T. Hong, S. D'Oca et al.

Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings.
ENERGY AND BUILDINGS – 2015

A critical review on the most updated advances in investigations and applications of energy-related occupant behavior in buildings, presented in journals form from 2013 to February 2015, was conducted as part of this doctorate, in collaboration with the two Annex 66 operating agents from LBNL (Berkeley, US) and Tsinghua University (Beijing, China). Results are presented as in Hong et al. [Paper 1] (Hong et al. 2015)

The study confirms significant improvements have been achieved in three main thematic areas: data collection, analytical and modeling methods, and simulation techniques to quantify the impacts of the energy-related occupant behavior and to provide insights toward energy saving behaviors and robust architectural design (Figure 1)

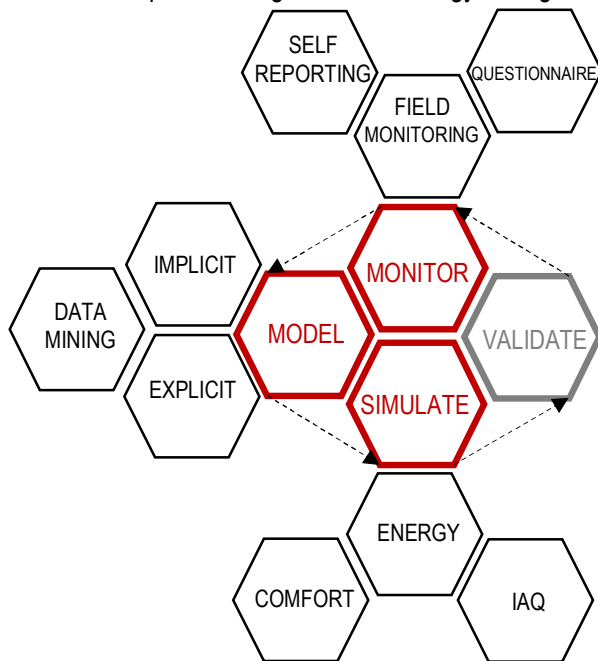


Figure 1. Key research areas of the occupant behavior research (Hong, D'Oca et al. 2015).

From the data collection front, the article highlights the diffusion of innovative data driven techniques to investigate occupants' interaction with building technologies such as real-time remote sensing, responsible of an intensification of human sensitive data information than ever before.

On the analytical and modeling front, advanced statistical, data mining, and stochastic modeling methods are being developed and applied to extract behavioral models from the experimental data. On the modeling front, a survey circulated to experts in the field among the Annex 66 community in 2015 (Hong et al. 2015) confirmed that among researchers, energy modelers and software developers, no common consensus has been reached yet on the standardization of modeling approaches, simulation tool usability and documentation or interoperability issues. Significantly, none of the surveyed experts appeared satisfied by the quality of existing models of energy-related behavior in buildings. As one of the main conclusion, the paper argues the cognition of the human factor in building energy uses is still insufficient, leading to inappropriate over-simplification and hence limited effective outcomes. At the current state, is this deficiency in standardization in data language, modeling procedures and consistent simulation methods, which is pushing the research community towards the pursue for a common scientific agreement to assure the general validity of studies of energy related occupant behavior in the building sector.

Energy-related behavioral studies reviewed during the three years research – conducted in the context of this PhD dissertation and published in Paper 1 (Hong, Taylor-Lange, et al. 2015) – covers both residential and commercial building occupant behavior. Substantial differences in energy-related behavior appeared intrinsically to these two diverse building typologies, such as activities conducted by the occupant, and their relative energy intensity level, the type of indoor conditioning system and its system controls and control logic. Also, the different scenario for individual and collective decision-making process leading to energy-related behavior emerges.

Furthermore, dissimilar comfort requirements, habits, motivation and drivers leading to interacting with control systems need to be accounted, among others, when observing, analyzing, modeling, simulating and engaging occupant behaviors in residential and commercial buildings. Review of journal articles published in the period from 2013 to February 2015 highlighted some recent advances and improvement in these paramount areas of investigation. Researchers have devised various approaches to assessing the impact of occupant behavior on building energy performance. A stochastic approach to representing occupant behavior has recently gained popularity, in contrast to the static description of occupant behavior based on assumptions made using fixed profiles. This new approach accounts for the fact that occupants do not always make logical choices and act stochastically rather than deterministically.

In order to study occupant behavior based on facts and not hypothesis, rigorous observation techniques must be applied. Methodological approaches – one more objective (field monitoring), one more subjective (self-reporting and questionnaires) as well as passive occupancy sensing – are used by the scientific community, to gain better understanding of energy related occupant behavior in buildings.

Innovation: Sensing the multidimensional sphere of human-building interaction**Field monitoring**

Occupant interaction with control systems is usually attained by monitoring window, blind, shades states, recording TRV (thermostatic radiator valve), AC thermostat set points, presence detectors such as motion sensors, intelligent control of building systems and real-time building visualization, security systems, PIR (passive infrared) sensors, ultrasonic detectors for light switching, and smart/wireless electric outlet meters. In almost all of the published experimental studies, observations of occupant behavior are coupled with 'primary indicators' such as indoor and outdoor environmental conditions. This includes data from a large array of field sensors (thermometers, anemometers, globe thermostats, CO₂ sensors, lux meters, photometers, etc.) as well as from weather stations (outdoor temperature and relative humidity, wind speed, rainfall, solar radiation and solar hours, etc.).

Occupant behavior can also be indirectly monitored by sensing 'secondary' environmental variables, parameters or actions and then performing extrapolation information. Relevant secondary indicators include the CO₂ concentration level, other tracer gas techniques, or metering the building energy flows. Surrogate information on energy-related behaviors can be deduced by using already available data such as occupancy derived from light switch sensors, computer switches, IT (information technology) infrastructure, and from equipment load profiles. Other widespread techniques to monitor control system state or occupancy movement and presence include imaging analysis such as time-lapse photography taken from the exterior building façade as well as camera-based and internal personal visual survey, such as personal building walkthroughs.

Questionnaires and self-reporting

Occupant behavior is not an isolated mechanical phenomenon, but rather a combination of driving forces that must be analyzed in relation to each other. Simply gathering a time-series data of past events might fail to capture the more complex motivational sphere driving occupants to interact with their indoor environments. Direct active occupant sensing overcome such limitation allowing to investigate specific aspects of occupant behavior by using humans as sensors.

These measurements can be conducted in two ways: either by observing their behavior or asking the occupants to report about their satisfaction with the indoor environmental conditions and the usage of building components and system controls. This latter type of information on occupant presence and activities may be obtained from time-use surveys aimed at investigating the types of energy-related occupant behavior actions. As an example, occupancy in indoor spaces can be inferred by detecting movement and presence, but the same information can be self reported by users, without the employment of any additional sensors.

Another data collection approach is to use different interview techniques such as questionnaires web-based questionnaires, computer-assisted telephone interviews or mail surveys. Questionnaire surveys are often used to identify the most important factors affecting occupant interactions with building control systems including: window opening behavior, the use of heating and cooling, solar shading and blinds, electrical lighting and equipment. The surveys are typically carried out by sending out invitations to a consistent amount of building occupants, which are representative of the building population. Subjects are asked about preferences in control system settings and repetitive actions. Often self-reporting techniques are used to record the human-building interaction when direct monitoring is not allowed. Data on occupant behaviors and preferences are typically coupled with information on dwelling characteristics, meteorological and census data (when available).

Lack of trustworthiness of occupant's self-reported actions and answers to questionnaire surveys has been largely advocated as a limitation of such approach. Time of use survey and questionnaire have been often criticized because people experiencing fatigue in tracking and reporting behaviors and actions over time. Responses might be biased by the so-called Hawthorne effect in human psychology – also referred as the "observer effect" – as a type of reaction in

which subjects modify or improve features of their behavior in response to their awareness of being observed (McCarney et al. 2007). However, occupant survey solutions overcome the key barriers to the adoption of the state-of-the-art sensing technology, including cutting the high initial cost of installation, operation, and maintenance of sensors, the difficulty of integration with existing BMS systems.

Moreover, **in order to understand fully occupant behavior, based on facts rather than hypothesis, questionnaire survey emerged as optimal tools** for discovery of a layer of social, contextual and group interaction constructs related to driving forces and individual motivations. In addition, main differences in OB can be identified by different countries, cultures, and climates. As part of this PhD study, a general guideline highlighting the different variables within the building that need to be monitored to capture the necessary information to analyze different behavioral actions was proposed in Hong et al. [Paper 1].

Passive occupancy detection

Apart from traditional in-situ measurements and large-scale survey, technology advancements are setting the stage of innovation in the field of occupancy detection in building spaces. Cutting-edge technologies can nowadays enable sensing and recognition of human presence, movement, and gestures leveraging on existing wireless sensor networks. Such human observation methods are grounded on virtual-reality technologies such as the Kinect technology (Pu et al, 2013). Fine-Grained Indoor Location of multiple occupancies can be provided by systems using MIMO (multiple-input, multiple outputs) techniques to track occupants roaming inside the building spaces via a wireless system.

Observation of such type demonstrates being effective in making almost ubiquitous, real-time and fine-grained pinpoint of occupants spread out over an indoor office environment, without the need of any additional sensing device (Xiong and Jamieson, 2013). Wi-Fi signals allow detecting human presence and movement also through walls (Wilson and Patwari, 2011), (Adib and Katabi, 2013), by using RF Body reflection and through-wall imaging (TWI) techniques. A 3D occupant motion tracking system (Adib et al., 2014, 2015) have been recently built on the advancements in traditional RF-based localization, i.e. using antenna arrays, information channels or backscatters. Innovations are brought about in terms of localizing human bodies leveraging radio signals reflected from the human body directly, without requiring the users to hold receivers or additional devices (Xi et al, 2014).

Moreover, techniques as eye tracking technology (ETT) and facial expression recognition have been recently adopted for gaining a better understanding of occupant interaction with human-building communication interfaces and sensing occupant intention and preferences. Eye tracking technology (ETT) has been broadly applied in the medical and cognitive field since the 90's (Rayner, 1998). Just more recently, it has found its way into the consumer research arena in light of the innovative contribution in the psychology domain of behavior. Reader might refer to (Wedel and Pieters 2008, Holmqvist et al., 2011) for a comprehensive research review and to for a comprehensive guide to methods and measures.

Outcomes: Critical review of OB sensing techniques

Innovative sensing techniques of occupant behavior in buildings should not merely focus in monitoring individual behaviors – and influencing factors. Conversely, inventive research needs to focus on developing observation methods of collective and social conventions shaped by geographical context, culture and norms, driving occupant behavior, as they are crucial in fastening behavioral patterns, with different consequences for building energy consumption and indoor environment comfort.

In order to understand fully occupant behavior, based on facts rather than hypothesis, a research conducted in the context of this Ph.D. study highlighted questionnaire surveys as optimal tools for discovery of a layer of social, contextual and group interaction constructs related to driving forces and individual motivations (Belafi et al. 2016 submitted). However, with respect to the actual state of the art, some contextual and OB related gaps emerged (Table 1).

Table 1. Summary of research gaps, state of the art and innovation in OB survey (Belafi et al., submitted).

	RESEARCH GAPS	State of the art	Innovations
contextual	geographical distribution	independent studies in Europe, US, China, Japan	provide international data coverage and comparison
	time update	survey updated to 2010	provide better and more updated data coverage, ask new and more relevant questions we care about today
	type of action	survey on one/two adaptive actions	survey on a wide spectrum of adaptive actions
	drivers	limited knowledge, an independent literature review on specific behaviors	broader and transversal understanding of the motivational sphere of occupant energy-related behaviors in office buildings
	group behavior	lack of knowledge on how people make a decision	provide new knowledge on the behavioral interaction among social groups in office environments
OB related	order of action		provide new knowledge on the order of action undertaken in order to restore comfort condition (thermal, visual, IAQ)

With respect to the *contextual gaps*, an unbalanced geographical distribution is observed among independent studies, mainly deployed in Europe, US, China, Japan. There is a limited number of large-scale transversal surveys carried out worldwide, and these focus more on measuring and predicating human comfort rather than investigating occupant behavior and motivational drivers. Consequently, the current literature lacks the general understanding of differences in occupant behavior in diverse cultures, countries, and climates. Most of the reviewed questionnaire surveys were carried out before 2010 and since then both office and residential appliance usage has changed significantly. In such a view, the improved survey will provide better and more updated data coverage, asking new and more relevant questions we care about today.

With respect to the *behavioral gaps*, since the 70's, researchers aimed to uncover the variables driving occupants' comfort satisfaction, need, acceptance and energy concerns. For these, social science provided quantitative methodological descriptions on how to develop survey research related to human subjects. Existing surveys typically focused on only one or two specific occupant action type, while surveys discovering the correlation on a wide spectrum of adaptive actions are needed. Similarly, still limited information is provided on drivers behaviors by independent literature reviews. At the current state, arbitrary conclusions are drawn from scattered and limited national datasets on occupant behavior drivers that can be considered valid all over the world. The order of magnitude occupant behaviors

differ between cultures, countries, and climates is still little understood. Finally, no study so far provides knowledge about action undertaken by the occupant in order to restore comfort condition (thermal, visual, IAQ) when exposed to certain indoor and outdoor variables. In addition, energy-related group behavior has been little observed and understood, and innovative insights on the behavioral interaction among social groups in office environments are needed. To bridge such gaps, a broader and transversal questionnaire survey is intended to enlarge the understanding of diverse occupant energy-related behaviors buildings.

Outcome: Methodological guidance for future surveys

By and large, the consistency of behaviors among cultures, climates, social and contextual interactions must be evaluated by dedicated model validation procedures. Similarly, a behavioral survey should endeavor for seeking uniformity of characters. Reporting plausible general behavior of a group of people might be more significant than exactly describe individual and isolated behaviors. Further advancements of behavioral surveys must strive to understand how to represent the social and contextual interferences of group behavior.

Finally, direct subject questioning might overcome constraints of physical sensing technique to gather insights of multiple behavior interactions, i.e. the order of actions typically performed by the occupants to restore or bring about comfort conditions. With any doubt, a trade-off between data accuracy and scalability is hence needed for achieving high impact results and bridging the credibility gap of energy efficiency in buildings. By conducting a new, large-scale international transversal survey, many questions of our field can be answered.

A better understanding of an occupant's adaptive actions would support policy makers, designers of the construction industry. Results can provide qualitative and partly quantitative data for occupant behavior modeling tools used in BEM. In the big picture, the future of occupant behavior research calls for one standardized practice, which necessarily encompasses a multidisciplinary approach to diverse fields of investigation. In this view, insights from social practice theories and techniques must be acquired to deploy robust and unbiased questionnaire surveys. Experimental subject observation methodologies, as well as techniques of data evaluation need to be established at the very beginning of the questionnaire design. This will ensure to provide universally acceptable information, knowledge, and insight on energy-related occupant behavior in buildings.



DEFICIENCY OF EFFECTIVE ANALYTIC TECHNIQUES PROVIDING USEFUL KNOWLEDGE ON OB IN BUILDINGS

HOW TO TRANSLATE BUILDING AND HUMAN INFORMATION INTO USEFUL KNOWLEDGE?

- PAPER 2 ● **S. D'Oca**, T. Hong.
A data-mining approach to discover patterns of the window opening and closing behavior in offices.
BUILDING AND ENVIRONMENT 11/2014; 82
- PAPER 3 ● **S. D'Oca**, T. Hong.
Occupancy schedules learning process through a data mining framework.
ENERGY AND BUILDINGS 02/2015; 88
- PAPER 4 ● **S. D'Oca**, S.P. Corgnati, et al.
Testing Socio-Economic Demographic Variables on building energy consumption scenarios at the urban scale in Italy. Proceedings of ClimaMed– 2015, Juan-les-Pins, pp. 1-8

4.2 OB Analyzing

“An interdisciplinary field bringing together techniques from machine learning, pattern recognition, statistics, databases and visualization.”

– Cabena

State of the art limit of research	Unabridged research questions	Innovations	Outcomes	Field of Research
Deficiency of effective analytic techniques providing useful knowledge on occupant behavior in buildings	How to translate building and human information into useful knowledge?	Occupant behavior data analytics	Data mining techniques to discover patterns of energy-related building-human interactions in big data set	OB Analytics

With the growing usage and technology development of IoT connected devices in smart buildings and the increasing trend in self-monitoring, large amounts of behavioral data will be available in the building sector. Traditional methods of turning data into useful knowledge require data cleaning, analysis and interpretation. However, such manual data analysis often becomes impractical, slow and expensive as data volume grows exponentially.

How to effectively translate building and human information into useful knowledge driving energy efficiency in building is still an open question.

In view of these facts, researchers in the field of machine learning, pattern recognition, databases, statistics, artificial intelligence, knowledge acquisition and data visualization, (Huebner et al. 2013, Fayyad et al. 1996) have focused their attention on the Knowledge Discovery in Databases (KDD). This presents an excellent opportunity for data analytics applications to discover new insights on the human-building interaction. The KDD involves the application of the following six steps (Figure 1):

1. *Data selection*: Creating a target data set, or a subset of variables, on which discovery is to be performed.
2. *Data cleaning and preprocessing*: Removal of noise or outliers, strategies for handling missing data fields.
3. *Data transformation*: processing records into meaningful features able to represent the dataset based on the goal of the task.
4. *Data mining*: Matching a particular data mining method for searching patterns in the data.
5. *Data interpretation and evaluation*: Determining appropriate parameters and inferring meaning to the mined patterns.
6. *Knowledge extraction*: Consolidating the discovered knowledge to be used for further applications

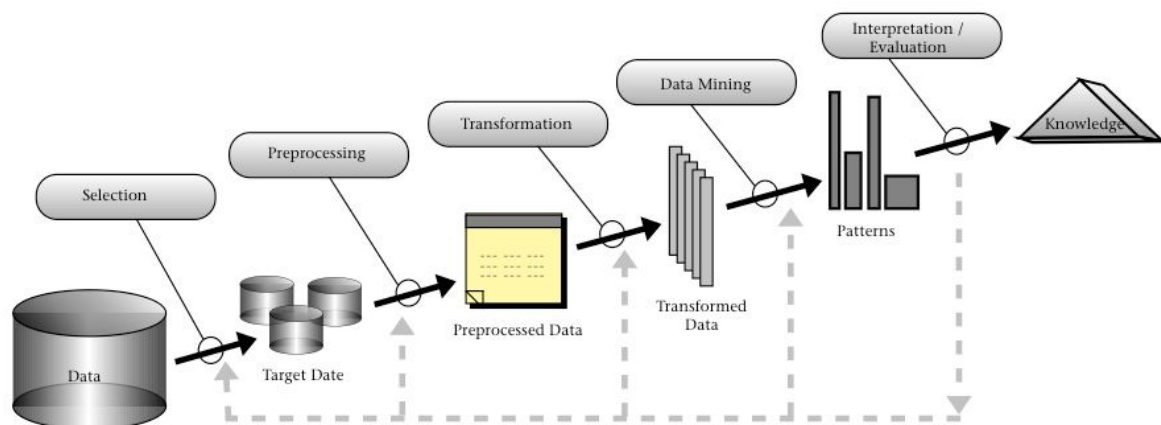


Figure 1. Graphical representation of the Knowledge Discovery in Databases (KDD) process. (E. Baralis, 2013).

Innovation: Occupant behavior data analytics

Data mining techniques are largely diffused into research fields such as marketing, medicine, biology, engineering, medicine, and social sciences to address the issue of patterns extraction from large databases (Han et al. 2007). However, application of data mining techniques to building energy consumption and operational data is still in an elementary phase. In recent years, the KDD process adopting data mining techniques has been increasingly used in the building science area, to investigate occupant behavior patterns or to analyze building automation systems and building energy performance (Lee et al. 2011; Yu et al. 2010; Yu et al. 2011; Yu et al. 2012; Feng et al. 2015; Christoph Morbitzer, Paul Strachan 2003; Zhao et al. 2013; González et al. 2008). In this context, data mining emerged a useful technique to elaborate huge samples of data extrapolating significant information. It currently leads the way to automatically analyzing huge volumes of data, which might be used to extract interesting, useful, and previously unknown knowledge from building and occupant behavioral data.

Preliminary studies showed data mining is a powerful analytical approach in providing insights into energy pattern related to the occupant behavior, facilitating evaluations of building saving potential by improving users' energy profiles as well as driving building energy policy formulation. Data mining techniques are used to learn user preferences, habits and patterns of occupancy and interaction with control systems. Real-time communication of such qualitative and quantitative knowledge provides occupant's with better information on the drawback of their choices in terms of comfort requirements on overall energy consumption and building energy performance. Such innovative behavioral models can be used as advanced inputs in virtual (simulation) and real-world (control communication) and real-time environments (energy visualization).

Research conducted in the context of the PhD studies applied the KDD data mining process to extrapolate information on behavioral patterns from measured building data. Systematic data-mining methodologies (Cluster Analysis, Association Rules, Decision Tree, Rule Induction) have been applied, along with the open source software Rapid Miner Studio, to obtain association rules segmenting building occupants characterized by similar behavioral patterns into user profiles, which can be further implemented as occupant behavior advanced-inputs into building energy simulations (Below et al. 2005).

Outcomes: Data mining techniques to discover patterns of energy-related OB in big data set

Using the Knowledge Discovery in Database (KDD) methodology, two data mining learning processes are proposed to directly extrapolate (a) windows opening/closing and (b) occupancy behavioral patterns from a given data set of 16 offices in a natural ventilated office building with 10-minute interval data over two complete years of a dozen measured indoor and outdoor physical parameters as well as occupancy presence and occupants interaction with window openings. Clustering procedures (Davies and Bouldin 1979), decision tree models (Breiman et al. 1984, Quinlan 1987) and rule induction algorithms are employed in order to obtain distinct energy-related behavioral patterns which constitute a base for association rules segmenting the building occupants into working user profiles. Final goal is to provide new knowledge able to drive different energy conservation strategies as well as robust design recommendations that may be appropriate to bridge the gap between predicted and actual energy performance of future sustainable office buildings.

Moreover, the KDD (Knowledge Discovery in Database) methodology has been employed in order to extrapolate valid, potential useful and understandable knowledge from the information related to GIS public census socio-economic data of an urban district located in Torino, Italy. Hence, energy model scenarios are drawn to represent the impact of different building occupant profiles over mid-long term building energy retrofit scenarios at the urban scale.

Scalability of solutions is one of the most critical point in bringing human in the loop of pattern mining. Results of the mined occupancy schedules, window opening rules and socio-demographic variables are circumstantial to the case study buildings and do not represent the complete set of patterns that can be derived within the given data sets. Nevertheless, they characterize the most compact, physical meaningful and high quality set of patterns that can be derived with satisfactory performance. Moreover, the proposed data mining frameworks are generic enough to be possibly applied to new behavioral and stratified data sets providing solutions to direct specific operation, maintenance and cost-optimal retrofit strategies, both at a building and at block of building level.

The international research community is investigating the most effective methodologies to represent occupant behavior diversity – e.g., clustering, combining all data to make a model, combining data just from each occupant to make a model, etc. – when implanting the behavioral variables in building energy performance simulations and forecasts.

Paper 2

S. D'Oca, T. Hong.

A data-mining approach to discover patterns of the window opening and closing behavior in offices. BUILDING AND ENVIRONMENT 11/2014; 82

A study was conducted in the context of this PhD dissertation in order to identify valid, novel, potential useful and understandable patterns of window opening and closing behavior in offices.

A three step framework is proposed - as in D'Oca et Hong, 2014 - as an improvement of the notion of window opening behavioral patterns not only as merely statistical relevant clusters based on the frequency of openings, but also incorporating the driver-response conditioning dimension with typical window opening habits. Statistical analysis and data-mining techniques were applied to measured building energy and environmental data of a given data set. (Figure 1).

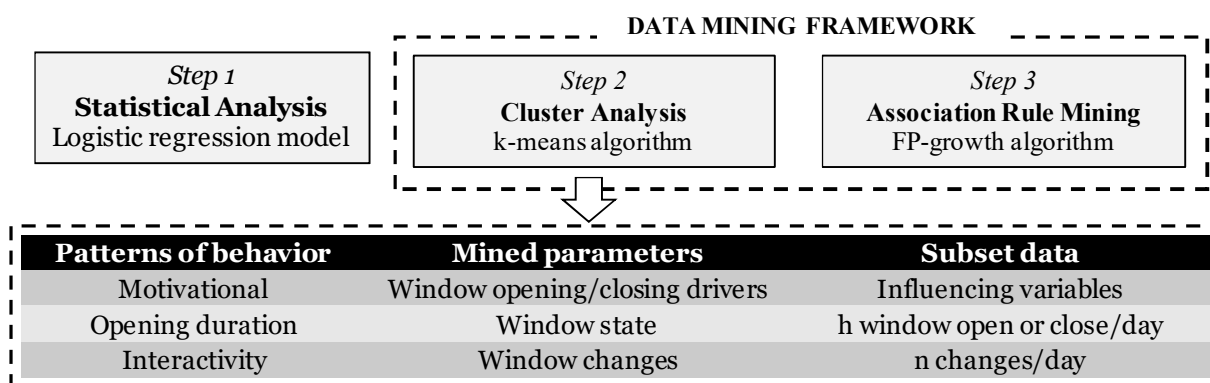


Figure 1. Proposed window opening learning framework (D'Oca et al, 2015)

- In step 1, a statistical analysis technique (logistic regression) was applied to the given data set. The goal was to discover the factors (variables and coefficients) influencing window opening and closing behavior.

A two steps cluster-then-association rules mining approach was applied to the given data set.

- In step 2, clustering procedures were employed in order to obtain distinct behavioral patterns. The goal was to estimate the motivational, opening duration, interactivity, degree of opening and behavioral patterns. In this aim, the research was estimating why (*motivational* pattern), for how long (*opening duration* pattern), how often (*interactivity* pattern) and how much (*position* pattern) working users open and close windows in offices of the same building.
- In step 3, the clustered patterns constitute a base for association rules segmenting the building occupants into typical office *user profiles*.

From driving factors to motivational patterns of behavior.

Factors influencing window opening and closing, which could be named under the general term “drivers”, are the stimuli leading to a reaction in the building occupants in ways to restore their comfort with respect to natural ventilation. Window operation is not only influenced by perceived thermal condition, but it is also seen as a response of sensed indoor air quality, external (outdoor temperature, solar radiation, wind speed, rain) and internal (indoor temperature) environmental conditions as well as contextual factors (window type, time of the day, season of the year) and personal and cultural preferences. Different time scales of time dependent parameters such as 1) season of the year time 2) day of the week and 3) time of the day, were included in the statistical analysis as predictor of the window opening and closing probability.

Moreover, window and occupancy were expressed in terms of 4) window state (open/closed) 5) occupancy state (present/vacant) and 6) window and 7) occupancy change of state. These predictors, even if closely related to the same parameters, were not surrogates of the others and were not duplicative of the same action. Instead, they were indicators of time dependence, occupant presence and movement respectively. Altogether they describe the intricate dynamics of different occupant behaviors in buildings. In our view, this overlap provides clarity in describing the complexity of occupant behavior and addresses the inadequacy of current practices based upon simplistic standardized schedules and input.

From the analysis it emerged that top drivers for window opening and closing were physical thermal (indoor air temperature, outdoor air temperature) and time-dependent contextual (time of arriving and leaving the office) parameters, apart from occupancy presence. These results strengthen the belief that not only physical factors, such as indoor and outdoor environmental parameters, influence human energy behavior, but also non-physical drivers, such as personal preference, habit, context and attitude, play an important role in understanding occupant behavior.

From occupant behavior to user profiles

Clustering procedures were employed in order to analyze different aspects of the window opening and closing behavior. The goal was to estimate why, for how long, how often and how much similar patterns of occupant open and close windows in offices of the same building. In this aim, the research was clustering 1) motivational, 2) opening duration, 3) interactivity and 4) degree of opening position behavioral patterns which would further constitute a base for association rules segmenting the building occupants into attitudinal typical working user profiles. From the information gained by the 12 rules mined, two typical working user profiles were drawn. User α was a mainly physical environmental driven working user type which tends to open the window for short periods of time (0.04 - 0.7 hours/day), interacting infrequently (on the average in between 0.7 and 0.04 times per day and usually preferred small openings (< 0.3 degree of tilting angle). On the other side, user β was mainly contextual driven working user type which tended to open the window for longer periods (on the average from 1.0 to 2.2 hours per day), interacting more frequently (on the average in between 1 and 1.7 times per day) and usually preferred intermediate openings (< 0.6 degree of tilting angle).

More detailed outcomes and discussion of the proposed window opening learning framework are presented in D'Oca and Hong [Paper 2].

Paper 3

S. D'Oca, T. Hong.

Occupancy schedules learning process through a data mining framework.

ENERGY AND BUILDINGS 2015

The KDD data mining process was employed to extrapolate information on occupancy schedule patterns from measured building big data streams (Figure 1). A three-step data mining method was applied to a data set to provide insight into patterns of occupancy in office buildings.

- In step 1, a data set of 16 offices with 10 minute interval occupancy data over a 2 year period is mined through a decision tree model that predicts the occupancy presence.
- In step 2, a rule induction algorithm is used to mine a pruned set of rules on the results from the decision tree model.
- In step 3, cluster analysis is employed to obtain consistent patterns of occupancy schedules representative of typical single office working user profiles.

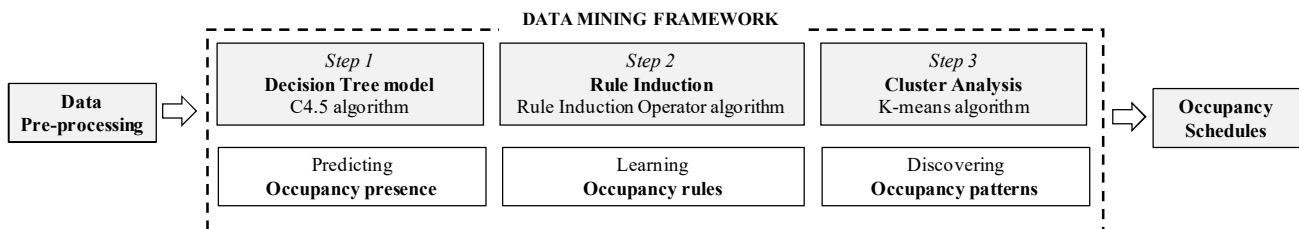


Figure 1. Proposed occupancy schedule learning framework (D'Oca et al. 2015)

The results of this study showed the occupancy patterns in single offices were not assigned to the same behavioral cluster every day, meaning that working profiles may vary broadly during different working days. A conspicuous variation up to 60% in the hourly occupancy rate was noticeable among patterns of occupancy especially during office arriving or leaving time. Furthermore, the clustering of typical office working activities such as working stable from the office, moving (arriving or leaving) from the office and taking breaks, such as having breakfast or lunch, highlighted that the average breakdown of hours spent every day by the monitored users in the single office space may differ broadly, as well as a significant shifting in the time the occupancy pattern activity/presence/ intermediate absence was occurring. Also, the occurrence occupants working over typical scheduled time emerged as phenomenon occurring frequently, nonetheless such patterns are omitted by using fixed deterministic occupancy schedules. This finding greatly affects appliance, lighting, plug-load, system controls and therefore building energy consumption. Finally, the proposed methods in this study identified rules of occupancy and archetypal user profiles for which different energy conservation strategies, as well as building design recommendations, may be appropriate. Characterization of the probability of an office being occupied at a specific season of the year, day of the week and time of the day will enable the more accurate development of building energy models. The results supported the assumption that occupant stochastic behavior and presence cannot easily described by means deterministic 24 hour schedules. Instead, more accurate profiles having the same patterns of occupancy of real building users are required to close the gap between predicted and actual building performance.

The future applications of the proposed method to discern occupancy schedules and their implementation into a building energy modelling programs, like Energy Plus or IDA-ICE, would strongly support the investigation of the impact of typical working occupancy patterns on design and operation of office appliances and control systems. In this context, further investigations are suggested to uncover cost-effective, applicable and reliable best practices and solutions supporting energy efficiency policies and decision makers on how to incorporate patterns of human movement and actions into behavioral models, with the aim of bridging the gap between actual and predicted energy performance in buildings.

More detailed outcomes and discussion of the proposed window opening learning framework are presented in D'Oca and Hong [Paper 3].

Paper 4

D'Oca, S.P. Corgnati, et al.

Testing Socio-Economic Demographic Variables on building energy consumption scenarios at the urban scale in Italy,

Proceedings of ClimaMed– 2015, Juan-les-Pins, pp. 1-8

In this study, the KDD (Knowledge Discovery in Database) methodology has been employed in order to extrapolate valid, potential useful and understandable knowledge from the information related to GIS socio-economic, building characteristics and historical energy consumption data of an urban district located in Torino, Italy

Public available GIS census statistical data were collected among 2012 and 2013 over the population of four census areas corresponding to four reference blocks of buildings. Supplementary details of the reference buildings are given in D'Oca et al.

Data on socio-economic and demographic variables such as education level, employment, ownership type and age (Table 1) are clustered by means a k-means algorithm, in order to find homogeneous archetypal user profiles among the reference blocks of buildings

Table 1. Gathered socio-economic and demographic variables: education, employment, ownership type and age (D'Oca et al. 2015)

Education level	Employment level	Ownership type	Population Age
Bachelor/master degree	Employed	Private dwellings	0-24 years
High school diploma	Unemployed	Rented dwellings	25-49 years
Middle school certificate			50-69 years
Primary school certificate			>74 years

Results of the cluster analysis showed a homogeneous distribution of the “Population Age” socio-demographic clusters, the four reference blocks of buildings. Specifically, the analyzed district emerged mainly populated by users aged 50-69 years old. A consistent pattern also emerged among the socio-demographic clusters for “Education Level” and “Employment Level”, while a wide dispersion arose with reference to the “Ownership type” (private owned or rented) of the dwellings located in the reference blocks of buildings.

Once homogeneous clusters of archetypal user profiles were drawn, the impact of the Socio-Economic Demographic Variables have been evaluated against the feasibility of retrofit measures at the urban scale. Final goal was to assess the renovation penetration potential on the considered district, based on some identified characteristic of the building occupants.

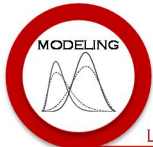
In a first step the global potential is calculated (considering all the buildings to be refurbished), while in a second step the impact of cluster characteristics on the feasibility potential is quantified. As appraised in the previous session, most the chosen socio-demographic variables (education level, employment level and population age) are homogeneously distributed within the district. Moreover, their level do not impact negatively on the refurbishment potential since most of the population has a work occupancy, a medium education level and the age range is not to high to avoid the possibility to invest. The only variable that differs meaningfully from a census area to the other is the ownership type. This consideration had a weight in the feasibility of renovation works: the probability that population living in rented dwellings will invest in energy savings measures is very low.

For this reason, and considering that rental occupants are not all concentrated in the same buildings, a feasibility index called “property factor (PF)” has been defined, dependent from users cluster’s that differs from a building block to another: A simplified energy models assessing the global energy savings potential (considering all the buildings to be refurbished) has been estimated. The considered interventions are the following: replacement of all windows for the lower classes, thermal insulation of the roof and the floor below the building, insulation of the walls.

Results of the cluster analysis demonstrated to affect for a total of +79% the energy savings potential deriving from the retrofit of the 21 district's buildings. Specifically in the areas characterized by low feasibility index, the cluster's analysis impact is very high. This result highlights the importance of including archetypal socio-economic user's profiles in the estimation of the feasibility and penetration of energy policy and measures. In particular, when this approach gauges at urban scale, it can support decision making in policy formulation by catching spatial differences in social conditions of citizens. Moreover, it might allow the promotion of tailored policies at individual district level, and the estimation of not only the potential of an intervention, but the real attended perception of the policy by investors.

The KDD methodology was employed to this study in order to extrapolate valid, potential useful and understandable knowledge from the information related to population and building census of an urban district. Moreover, clustering techniques were applied to provide advancements in the standardization of the quantitative descriptions and classification of archetypal occupant behavior profiles influencing building performance. Final goal of the proposed approach was to evaluate the influence of clusters of socio-demographic variables associated to some archetypal user profiles on the penetration of refurbishment actions and on the renovation technology adoption at the district level. Considering the case of energy planning at the urban context, diversity profiles must be general enough to be valid and applicable to the huge variety of energy-related behaviors and user socio-demographic characteristics.

Readers might refer to D'Oca et al. [Paper 4] for an extensive presentation and discussion of results calculation of the cluster analysis and the simplified energy model.



LACK OF COMMON AGREEMENT ON VALIDITY AND EFFECTIVENESS OF OB MODELING AND SIMULATION APPROACHES

WHICH ARE THE STRENGTHS, SHORTCOMINGS AND NEEDS OF OB MODELING AND SIMULATION METHODOLOGIES?

- PAPER 5 ● **S. D'Oca, S.P. Corgnati et al.**
Literature review and illustrative examples for modeling approaches of occupant behavior.
Submitted to JOURNAL OF BUILDING PERFORMANCE SIMULATION – May 2016
- PAPER 6 ● **T. Hong, S. D'Oca, et al.**
An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs Framework.
BUILDING AND ENVIRONMENT – 2015
- PAPER 7 ● **T. Hong, S. D'Oca et al.**
An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema.
BUILDING AND ENVIRONMENT – 2015

4.3 OB Modeling

“Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.”

– George & Draper

State of the art limit of research	Unabridged research questions	Innovations	Outcomes	Field Research of
Lack of common agreement on validity and effectiveness of occupant behavior modeling and simulation approaches	Which are the strengths, shortcomings and needs of the actual modeling and simulation methodologies?	Occupant behavior modeling and simulation information standardization	Updated critical analysis and standardization tools of modeling and simulation approaches for energy related occupant behavior representation in buildings	OB Modeling

Characterizing the intrinsic randomness of occupants' behavior is essential to improve the predictive accuracy of building simulation. Advances in building energy modeling engines allow a large array of the most widespread simulation tools (EnergyPlus, IDA ICE, ESP-r, DeST, TRNSYS, DOE-2) to input tailored advanced models of occupant behavior in dynamic simulations. However, a deficiency of a standardized method for describing and implementing energy-related models of occupant behavior in BEMs emerged. The objective of this section of the dissertation is to identify **which are the strengths and weaknesses of modeling and simulation approaches of occupant behavior**.

To this end, a critical literature review has been conducted of some identified existing model forms predicting state and state-transition of building components. Moreover, a standardized language to represent and communicate OB models in building energy simulation emerged as needed. Consistent schema and language are hence designed to provide enough flexibility for existing and future occupant behavior to be captured and implemented into building energy models in a consistent way.

Innovation: occupant behavior modeling and simulation information standardization

A present challenge deals with the oversimplification and transferability of existing occupant behavior models. Typically, the stochastic nature of the occupant is condensed into homogeneous and deterministic inputs, often ignoring the diversity and inter-dependency of various behavioral and seemingly stochastic actions. Also, model inputs are generally model specific, often selected based on the intent of the investigation study and hinges on user input assumptions. A critical review of the existing occupant-modeling concepts published in literature has been conducted as part of the PhD studies. [Paper 5]. Occupant behavior models typically refers to implicit or explicit models. Examples of each model type predicting: a) the states of the building components and b) the event (state-transitions) of the building components are described. Different ways of integrating occupant models in BEM programs are explored, and their weaknesses and strengths are identified.

Moreover, one of the key takeaways drawn from state of the art research is the deficiency of a standardized method for implementing and representing energy-related models of OB in building energy modeling (BEM) programs. By supporting a modeling agreement on such a technical structure simulation results become less difficult to compare, allowing the research community to attain general validity of OB simulation outcomes.

Based on extensive reviews of more than 130 journal articles publishing energy-related behavioral studies, an ontology framework is designed to provide the research community with a distinctive systematic approach to describe the energy-related behavior phenomena in buildings, based on Driver, Need, Action and Systems (DNAs) [Paper 6]. Grounded on the DNAs framework, a standardized eXtensible Markup Language (XML) schema is adopted to represent OB models (obXML) in building energy models. The obXML schema has intrinsic flexibility to represent numerous, diverse and complex types of occupant behaviors in buildings, and it can also be expanded to incorporate new types of behaviors [Paper 7].

By adhering to the obXML content and syntax in representing OB models, the simulation community will benefit from an internationally established data exchange format, which has been largely approved in several domain of building modeling.

Paper 5**S. D'Oca et al.**

A review of the occupant modeling approaches in offices with illustrative examples

Submitted to JOURNAL OF BUILDING PERFORMANCE SIMULATION – June 2016

User-defined models of occupant behavior are today widely implemented in current building simulation tools. However, this is still a non-trivial task, even for expert modelers. Several options are available, ranging from using pre-calculated deterministic inputs – so-called schedules – to the implementation of behavioral models as user function into the simulation engine. Diverse behavioral models capture building and occupant specific snapshot of reality, accordingly to dissimilar modeling methodologies. In the past two decades, researchers have introduced the basics of modeling human presence and behavior in buildings (Haldi and Robinson 2011) – particularly in office settings. However, the modeling methodologies remained fragmented amongst a large number of articles (Gunay et al. 2015).

Some key areas of general agreement emerge on modeling approaches of occupant behavior in building. First of all, human behavior is stochastic. This implies its description as standardized repetition of actions may not lead to truthful simulation outcomes. However, some statistically relevant trends in measured behavioral data can be observed. This infers pre-determined energy-related behavior in building can be substitute with statistical models, providing more accurate simulation inputs. Some high level trends can be spotted having statistical relevance, i.e. occupants opening the window when arriving the office or when driven by comfort requirements. Conversely, no matter the accuracy of model intrinsic validation, these discovered correlations remain circumstantial.

The objective of this paper, developed in the context of the IEA EBC Annex 66 activities, is to provide a critical review of the existing occupant modeling methodologies. To this end, a comprehensive survey of the state-of-the-art literature was conducted, and examples for each modeling approach were provided upon two data sets gathered from two office buildings in Ottawa, Canada and Hartberg, Austria.

The occupant models were categorized into three groups: (1) adaptive behavior models, (2) non-adaptive behavior models, and (3) occupancy models. The adaptive behaviors are occupant actions undertaken primarily to restore occupant comfort – e.g., light switch-on, blinds closing, thermostat use, window use, and clothing adjustments. The non-adaptive behaviors are actions mainly driven by contextual factors rather than physical discomfort – e.g., plug-in appliance use, light switch off, and blind opening. The occupancy models predict occupants' presence, arrival/departure patterns, and the duration of vacancy/occupancy periods.

In the reviewed literature, four different adaptive behavior model forms were found: (1) schedules, (2) Bernoulli models, (3) discrete time Markov models, and (4) discrete event Markov models. The formalisms classify whether the models predict the occupants' adaptive actions or the state of the building components with which occupants interact. The first two model forms were defined as implicit, and the last two were defined as explicit models (Hong et al. 2015).

Implicit models – ranging from average deterministic schedules to more intricate Bernoulli processes – predicts the likelihood of a building component state based on indoor or outdoor parameters and influencing variables, as proxy for occupant behavior. Explicit models – in a form of Markov models – includes more compound direct modeling methodologies incorporating the time or event dimension into the prediction function of a building component state-transition. Further, survival models introduce the time duration dimension as prediction variable of a building component state or state-transition.

Accordingly, the reviewed modeling approaches of occupant behavior can be summarized as follows.

Adaptive behavioral models

- Implicit: predict state of building components (proxy for behavior)
 - Schedules

- Bernoulli models
- Explicit: predict interaction with building component (actual behavior)
 - Discrete time Markov models
 - Discrete event Markov models.

Non adaptive behavioral models

- Building Schedules
- Occupancy Schedules
- Survival Models

Occupancy models

- Occupancy Schedules
- Discrete time Markov models
- Survival Models

Some key takeaways on strengths and weaknesses for the development and implementation of each model type follows are offered as outcomes of the presented research (Table 1) and discussed in the followings.

Table 1: Strengths and limitations of each reviewed and tested model type (D'Oca et al, submitted)

	Strengths	Weaknesses
Schedules (Deterministic models)	Can be used if developed for a similar building archetype.	Steady-periodic nature
	Easy to develop, interpret, and use in BPS.	Lack of transferability. Different design alternatives are not studied.
	Indoor or outdoor climate data are not required.	Limitations of the use cases lead to widespread misuse
	Acknowledges the relationship between occupancy and behavior.	Provides no insight about the user's adaptive comfort
		Neglect the connection between occupancy state and behavior.
		Limitations of the use cases lead to widespread misuse.
		Zone level arrival/departure patterns cannot be represented realistically.
Bernoulli Models	Indoor or outdoor climate data are not required.	Since dependency from explanatory variables, cannot be used for even identical buildings
	Provides some improvements in explaining the adaptive behaviors at different climatic conditions.	Same as the schedule-based models.
		They require concurrent occupancy and outdoor climate data.
Discrete time Markov Models	Transferability of other building types.	Stochasticity in the modeling results may not be easy to interpret.
	Ability to mimic the adaptive behaviors.	Concurrent indoor and/or outdoor climate data and occupancy data required.
		Dependence on fixed and prescribed timesteps.
Discrete event Markov Models	Same as the discrete time Markov models	Stochasticity in the modeling results may not be easy to interpret.
	Can tackle the timestep dependency issues	Need to predict the events triggering the simulation step accurately.
Survival models	Transferability of other building types.	Are continuous time random processes
	Elaborates the relationship between the vacancy state and behavior patterns.	Rounding errors can be significant when used with large timesteps in BPS.
	Predict the length of the occupancy/vacancy periods.	

Schedules (deterministic models)

The main advantage of using deterministic schedules of occupant behavior is their ease of use and application to a wide array of adaptive behavior and building types. Application of such “deterministic” models of adaptive behaviors provides energy consumption outcome respect to interaction with different building envelope components (windows, blinds, shades) and energy control systems (lighting, thermostat and AC adjustments, fan usage, etc.) for diverse building types (residential, commercial, education). For this reason, deterministic average models have been extensively embedded in BEMs.

Another advantage of deterministic average value models is that the replication of the behavioral phenomena is supported by empirical and experimental studies on responses of human physiology and environmental comfort theories (Ole Fanger 1970)(Dear et al. 1998). These have been introduced as recommended indices values for EU (UNI EN 15251) and US international specification for occupant comfort conditions and criteria (ASHRAE/ANSI 55, ASHRAE 90.1). Conventionally, building energy models use the deterministic assumption that occupants behave according to such standard design conditions – occupancy levels, ventilation rates, thermostat set points – illustrated by means schedules and threshold values. However, this steady-periodic modeling nature establishes correspondingly their main disadvantage.

One of the drawback of deterministic models is their intrinsic weakness in capturing diversity of individual behavior, demonstrated varying up to a factor of 10 in even identical buildings (Dong et al. 2013), as well as actual system operation and control of IEQ level. The same occupant may respond differently, on different occasions, even in response to identical stimuli; we may also encounter considerable differences in responses between individuals to identical stimuli (O'Brien & H Burak Gunay 2014)(Fabi, Andersen, S. Corgnati, et al. 2012). This randomness can have significant implications for building energy demands. Also, oversimplified assumptions might lead to inconsistencies between simulated and actual building energy performance (Turner & Frankel 2008), (D'Oca et al. 2014).

The strength of average values model form is that only a single data type is necessary to build it. It is easy to interpret for building operators and simulators. Data-driven average value models provide valuable insights that can help operators choose occupancy schedules or pinpoint recurring issues such as lighting or computers left on overnight or weekends. Simulators can incorporate them quickly in building models to represent lighting, plug load, and occupancy. The major assumption of this modeling approach is steady-periodicity. In other words, the model form establishes that the time of week or the month of year alone is adequate to make predictions for the occupant behavior and presence.

This assumption arises from the fact that occupancy and indoor and outdoor environmental factors that influence adaptive behaviors tend to recur in daily or seasonal cycles. However, when a building designer or operator wants to find out the outcomes of a design or a control strategy, the indoor climatic conditions that affect the occupants' behavior will inevitably change. For example, changing the glazing material and geometry, operable shading material and controls, lighting fixture and controls will play an unprecedented role over occupants' use of lighting. Because the average value models do not incorporate the indoor environmental proxies (e.g., work plane illuminance) to explain occupants' adaptive behaviors, these models will fail to mimic them under other building design and control scenarios.

Bernoulli Models

Regarding the Bernoulli processes, their nature to model behavior indirectly makes them insufficient to replicate the actual dynamic processes leading occupants to perform actions. This is typically true because models are developed based on observations of a building component states (for example window states), but not the actual actions on it (window opening or closing). In other words, these models do not describe an actual probability of window opening or closing, but a probability for a window to be found open, provided relevant physical parameters. Furthermore, Bernoulli processes ignore the particular patterns caused by occupancy events, like arrivals or departures of occupants. Instead, such models describe direct correlation between control system state and occupant behavior via some sort of correlation model. However, since adaptive behavior are implicitly modeled based on state of some building component assumed as proxy for adaptive actions, no need for human sensing, survey or feedback to build behavioral models is needed. This leads to avoiding occupants reporting monitoring fatigue over time or sensor placing issues. As a correlated drawback, incorrect formulation of the correlation assumptions might lead to unanticipated fallacies in predicting behavioral adaptation.

Discrete time Markov Models

Differently from deterministic and Bernoulli models, Markov models are explicit representation of occupant adaptive behaviors. Occupant models exploiting discrete-time approaches become popular among the research community because of the straightforwardness of pairing consecutive repetitive probabilities with some simulated changes in environmental conditions - at fixed time steps. This means Markov Models can couple repetitive probabilities with changes in environmental conditions at fixed time steps, making it an optimal modeling approach to be simulated in BEMs in discrete-time steps. In addition, discretizing adaptive behavior in fixed time steps allows the possibility of coupling multiple behavioral models, solving different prediction probabilities in the same BEM.

In fact, discrete-time Markov models provided the biggest improvement in the models informative value of BEMs among the building simulation research community. However, in reality, occupants' adaptive actions are events taking place at irregular time distance, which cannot be discretized over time. As an example, the improvement in models' informative value with the discrete-time Markov models, in contrast to the Bernoulli models, can be attributed to the fact that occupants tend to close their blinds when it is bright; but they tend to forget them closed when the ambient conditions change and the risk of glare diminishes. Discrete-time Markov lighting and blinds use models are able to mimic this better than the Bernoulli lighting and blinds use model, because they predict the light switch or the blind closing/opening actions instead of the light state or the blind occlusion rate.

Discrete-time Markov models – unlike the average value occupancy model – can represent the frequency and timing of the arrivals and departures. This makes such model form compatible with Markov occupant behavior models, as they explicitly require the presence information for the zone occupancy. The major drawback of this model form is the arrival and departure events are independent from each other. In other words, occupants may depart early when they arrive early; similarly, they may depart late when they arrive late. This model form fails to capture this pattern of behavior, if it exists. The other weakness of the discrete-time Markov models that utilize the ambient environmental conditions as proxies is that they cannot be transferred to other buildings because they neglect the influence of the fenestration geometry and material and the interior design over the indoor lighting distribution.

However, they can be useful for control-oriented building models intended for the same building they are derived from. A common issue regarding the discrete-time Markov models is their dependency on fixed and prescribed time steps. They only provide the likelihood of an event in the next time step. Although mathematically it is possible to modify their prediction horizons to maintain compatibility with other building, HVAC, and occupant models that require different temporal resolutions, the procedure is undocumented and consequences over the models' predictive accuracy remain unclear.

Discrete event Markov Models

Discrete-event Markov models link the calling points of an occupant action model to an external event. This modeling approach alleviates the modelers from most of the limitations of the aforementioned methodologies. It overcomes barriers of using fixed average values (deterministic model), implicit modeling adaptive action based on variables influencing state of building components (Bernoulli models), and discretizing adaptive behaviors in prescribed time steps – inherent in discrete-time Markov models. It is however, challenged by finding an appropriate event definition to replace the time step concept. Another limitation of this approach is that its predictive performance relies on the accuracy of the external events' predictions.

Survival Models

In survival models, the ratio of the “state” or the “state-transition” of an occupant behavior is modeled based on the variation of some identified stimuli. The limitation of this model form is that its predictive performance relies on the accuracy of the occupancy model to describe the zone level occupancy patterns. In contrast to average value model, the advantage of the survival model form is that it can be compatible with buildings with different occupancy patterns than it is derived from. While discrete-time Markov occupancy models may fail to capture potential dependencies between arrival and departure times – because they treat these variables independently – survival model form can tackle the limitations, by linking the timing of the arrival and departure events with each other.

Outcome: Updated critical analysis of modeling approaches for energy related occupant behavior simulation in building energy models

Characterizing the inherent randomness of occupants' behavior is integral to improve the predictive accuracy of building simulation. Data-driven stochastic models are developed upon statistical analyses of the occupants' behavior and environmental conditions, and they predict occupants' interactions with various building components - operating windows, blinds, and lights, and adjusting thermostats. Objective of this study was to identify the strengths and weaknesses of currently diffused modeling approaches of occupant behavior. Unfortunately, no general agreement of the best fit-for-purpose modeling approach exists.

To this end, after discussing literature review outcomes, studies conducted in the context of this PhD dissertation highlighted son key foundlings.

- The discrete-event Markov models overcome a wide array of weaknesses emerged among the other approaches
- The truthfulness and suitability of model selection is function of the specific use cases for occupant behavior modeling approaches.
- There is a need for an occupant modeling data repository where researchers can exchange open source and candid information resources. However, data privacy and disclosure remains a challenging matter in studying human subjects.
- The principal obstacle to the wider use of occupant behavior models remains the lack of quality-validated models to support the choice of the appropriate probability distribution for the random variables of the models.
- There is a need for tools and standardize methodologies to evaluate existing and new (e.g., ANNs, fuzzy logics, etc.) modeling methods
- There is a need for models of softer attributes (i.e., contextual factors, social norms, personal norms, multiple behaviors, etc.)
- Attaining better prediction of building energy consumption entails the implementation of such behavioral models into building energy models, despite the nature of the modeling approach.

More detailed outcomes and discussion of the proposed critical review are presented in D'Oca et al. [Paper 5].

Outcome: Critical analysis of representation formalisms of occupant behavioral models in building performance simulation programs

Advances in building energy modeling engines allow a large array of the most widespread simulation tools, such as EnergyPlus, IDA ICE, ESP-r, DeST, TRNSYS, DOE-2, to input tailored advanced models of occupant behavior in dynamic simulations. Typically, occupant behavior (OB) models are developed based on inhomogeneous variables and metrics. The selection of different drivers for similar occupant behavior models makes it difficult to compare the models and incorporate them into building energy modeling (BEM) programs. A recent review on modeling and simulation approaches of occupant behavior in buildings argued the problem of transferability of occupant models developed based on a selected observation study to different building models. In addition, one of the key takeaway drawn from the study is the deficiency of a standardized method for implementing energy-related models of occupant behavior in BEMs. Some key aspects hinder to such unachieved goal.

Shortcomings in the diffusion of OB models implementation in current BEMs are exacerbated from the non-trivial environment of common simulation engines, having unfriendly interfaces and requiring programming knowledge and specific code validation procedures to incorporate behavioral custom component models. Further, when behavioral model embedding is allowed via source-code alteration in current BEMs, each simulation engine supports specific data syntax and structure for occupant behavior input formatting (Figure 1).

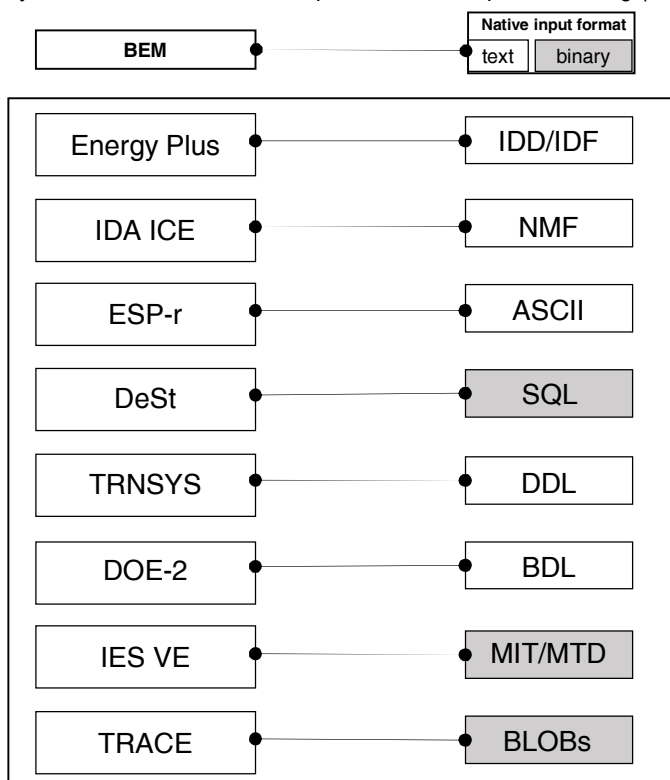


Figure 1. Summary of native input formats of principal BEM representing OB models (Hong et al, submitted)

EnergyPlus supports input files written in its native Input Data File (IDF) format. IDF files conform to the ASCII, the American Standard Code for Information Interchange, text based data format written using the Input Data Dictionary (IDD) semantics. To enhance flexibility of Energy Plus occupant behavior modeling capability, a co-simulation software has been recently developed by Hong et al (Hong et al. 2015). Accordingly, co-simulation in Energy Plus is performed by using a functional mock-up interface (FMI), to allow for direct coupling with various programs.

IDA ICE employs equation-based models based on the Modelica-like Neutral Model Format (NMF), making it straightforward to quickly expand the software with built-in models or by more complex user-customized functions.

However, newly created NMF OB models can only be shared with other IDA ICE users. NMF is ASCII text-based semantics for IDE ICE.

DeST binary-based SQL database to store user inputs. The SQL database allows the use of multiple data tables to represent user inputs for building components and systems, as well as OB models. Different tables are linked together using unique IDs or keys.

ESP-r simulation engine – namely “bps” – formulates by default binary results libraries in the ASCII text format. If a GNU libxml2 library is available in the simulation engine, simulation results can be exported into ASCII XML and comma-separated-value formats. Differently, in presence of a GNU libxslt library, the simulation engine can directly translate the XML result file into any ASCII format required by the modeler. Using the building control virtual test bed (BCVTB), users can link ESP-r with OB models implemented in other tools such as MATLAB, Simulink, Dymola and Radiance.

TRNSYS allows users to create stand-alone models having the TRNSED input file (.trd extension) format and syntax. The TRNSYS simulation engine is written using the FORTRAN programming language and uses a Dynamically Linked Library (DLL) system architecture to allow for a modular structure that can be extended around the core simulation engine called “IISiBat”, by adding new DLLs to the system. This allows TRNSYS users to create quite straightforward custom model components (e.g. to represent a new type of heating module) using a choice of DLL compiling programming languages including FORTRAN, Pascal, C, C++ etc.

DOE-2 supports the Building Description Language (BDL) ASCII text based input syntax, which is compatible with the conventions defined in both the C and FORTRAN programming languages. Expressions can include elements such as special BDL functions, math and logical operators, and logical structures. Manual entry of user customized BDL expressions requires a fairly detailed knowledge of the BDL text data structure.

IES VE is grounded on input files having MIT/MTD native binary format. However, the IES codes are not public, and modelers can't have direct access to MIT/MTD files in a text editor – such as for IDF files.

TRACE supports data serialized into closed-source binary BLOBs (Binary Large Object). Binary data are stored as a single entity in a Sybase relational database. One of the drawback of binary BLOBs is that, since the data source code is not available, inputs cannot be freely improved by modelers, input formats cannot be translated into different software architecture, nor can codes be adapted or modified to operate user-customized variants of the simulation software.

Further details on the OB models implementation approaches among current building simulation tools can be found in a correlated study developed in the context of this Ph.D. dissertation (Hong et al, 2016 submitted).

Adding advanced input models related to occupant behavior in most widespread BSP emerged as a complicated task. Energy modelers willing to implement behavioral models into current BSP must possess expertise in coding languages and acquire advanced knowledge of the simulation engine they are using (EnergyPlus, IDA ICE, ESP-r, DeST, TRNSYS, DOE-2). Firstly, this aspect may not be adequate to implement behavioral models in a software logic designed to replicate thermodynamic phenomena associated to the physical processes of the building systems and components.

Going further, outcomes of this study highlight the representation of occupant behavior models in building simulation programs (BSP) – based on text or binary syntax - is subject to limitations of characteristic input format semantics of each BPS program. Since no standardized language exists, other BPS programs cannot reuse behavioral models coded for a specific simulation program. Moreover, it become difficult to share implemented behavioral models even over users of the same BPS program, as advanced models are not embedded in the building energy models.

In this view, a shared ontology to describe occupant behavior inputs emerged as needed (see Paper 6). Consequently, a standardized input syntax grounding the OB model representation for implementation in building energy simulations is developed (see Paper 7). These developments are intended to avoid modelers losing control of the coding languages required for advanced model implementation in the diverse simulation engines. Also, they are intended to allow the maximum flexibility for more expert modelers to develop their OB models, which can be shared by the scientific research community and simulation users, over multiple BPS programs.

Paper 6

T. Hong, S. D’Oca, et al.

An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs Framework.

BUILDING AND ENVIRONMENT – 2015

Advancements in the standardization of the quantitative descriptions and classification of occupant behavior on building performance has been initiated by programs such as the IEA EBC Annex 66: Definition and Simulation of Occupant Behavior in Buildings. An ontology to represent energy-related occupant behavior has been outlined in a DNAs (Drivers, Needs, Systems, and Actions) framework, providing a systematic representation of energy-related occupant behavior in buildings (Yan & Hong 2014).

A homogeneous semantic information model for the representation of occupant behavioral models that enable interoperability of inputs and transferability of simulation outputs has been developed in the context of this PhD dissertation (Hong et al. 2015). The DNAs framework supports a consistent schema called obXML based on the XML (eXtensible Markup Language) designed to provide flexibility for existing and future occupant behavior to be captured and implemented into building energy models in a consistent way (Figure 1)

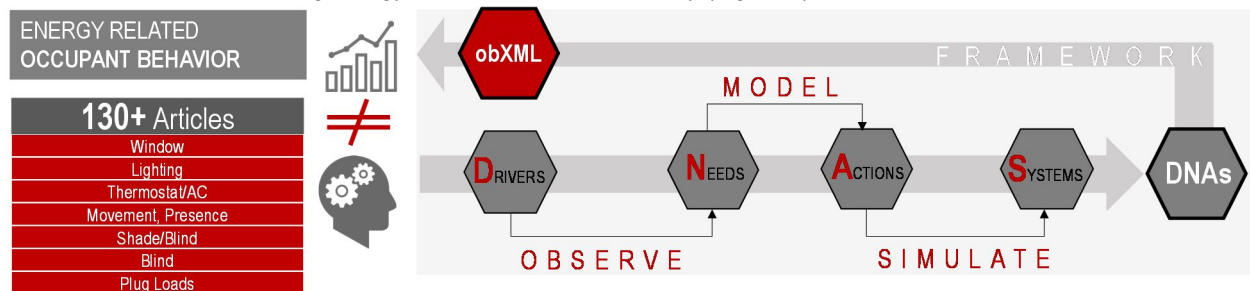


Figure 1. A schematic showing the integration of advanced data collection techniques with the DNAs framework and integrated into the obXML for occupant information modeling (Hong, D’Oca et al. 2015)

Over the last 40 years are several frameworks describing human behavior using a need-action-event cognitive process have been theorized in the literature. A review of principal human cognitive-behavioral frameworks have been conducted and published in Hong, D’Oca et al as in Table 1.

Table 1. Referenced cognitive framework of behavior

Acronym	Name	Author
PCT	Perceptual Control Theory	(Powers 1973)
HOS	Human Operator Simulator	(Wherry 1976)
CCT	Cognitive Complex Theory	(Card et al. 1983)
EPIC	Executive Process Interactive Control	(Kieras and Meyer 1997)
SOAR	State, Operator and Result	(Lehman et al. 2006)
ACT	Adaptive Control of Thought	(Anderson and Liebere 1998)
COGNET	Cognition as a Network of Task	(Zachary et al. 1998)
APEX	Architecture for Procedure Execution	(Freed 1998)
BRAHMS	Business Redesign Agent-Based Holistic Modelling System	(Sierhuis et al. 2007)

Please refers to Hong, D’Oca et al [Paper 6] for a further description of the nine cognitive-behavioral frameworks.

All these theoretical frameworks consider users as reactive agents instead of passive receptors within a contextual environment. In similar manners, the reviewed models try to capture the stochastic nature of the human cognition

process by describing the connection between the human ‘inside world’ inputs (drivers and needs) and the environmental ‘outside world’ outputs (actions and events). Most of the models capture the stochastic and reactive nature of human behavior in a complex environment, simulating users as agents acting in a specific space as a function of time. However, none of the models focus on energy-related behavior in the building indoor environment, framing the cognitive processes of the ‘inside world’ that lead building occupants to perform actions in the ‘outside world’, such as interacting with control systems in the building spaces, when driven by needs from the ‘inside world’. An initial concept of the DNAs framework was proposed (Turner & Hong 2013) as a brief introduction to the DNAs ‘Drivers e Needs e Actions e Systems’ concept.

A full ontology was hence developed as part of this PhD, as described in Hong, D’Oca et al [Paper 7] (Figure 2).

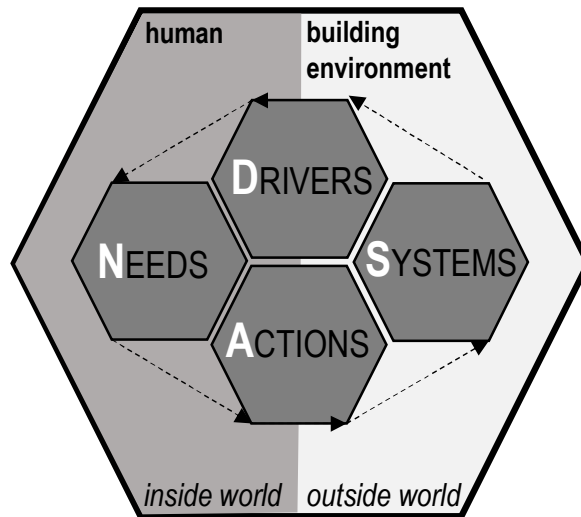


Figure 2. Four key components of the human-building environment interaction framework (Hong, D’Oca et al. 2015)

The impact of the behavior of the occupant (or groups of occupants) on building energy use, can be described using four main components, namely drivers, needs, actions and systems.

Drivers

Drivers represent the environmental and non-physical factors from the outside world that stimulate occupants in their inside world to fulfill a physical, physiological or psychological need. A driver prompts a building occupant to perform either an action or to interact with a building system, impacting the energy use of a building (Figure 3).

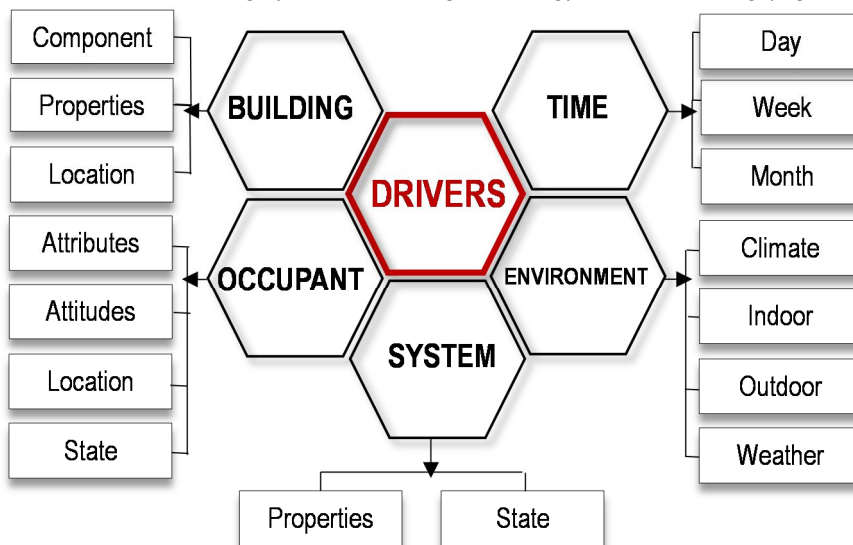


Figure 3. The DRIVERS component of the DNAs behavioral framework (Hong, D’Oca et al. 2015)

Within the topology of drivers, five main categories were identified, (i) building, (ii) occupant, (iii) system, (iv) environment and (v) time.

- i. The building category embraces the physical properties of the building itself that can act as drivers (i.e. building's orientation, construction material, floor layout, location of the building, etc.) (Goldstein et al. 2011).
- ii. Occupant's features dictate how an occupant behaves and their response to environmental drivers and hence, how they interact with building systems (i.e. to age and gender (Karjalainen 2007), (Indraganti & Rao 2010), as well as physical mobility (Parsons 2002), etc.)
- iii. System state of a building system (i.e. state of windows, shades, blinds, and thermostat) acts as a statistically significant predictor of the probability of an occupant interacting with the system itself (Robinson et al. 2011; Wilke 2013)
- iv. Environmental factors such as climate, weather and indoor and outdoor conditions (e.g. air temperature, humidity, solar radiation, IAQ) are all fundamental drivers behind the response of occupants to their environment (Fabi et al. 2012; Gunay et al. 2013)
- v. Time-driven attributes (i.e. time of day, day of the week, season of the year, etc.) are central to the presence and location of occupants in a building. Also, they affect personal habits, needs and impact on occupancy presence or equipment usage (Andersen et al. 2009; Hori et al. 2013; Gram-Hanssen 2014)

Needs

Needs represent the physical and non-physical requirements of the occupant's inside world that must be met in order to ensure the satisfaction of the occupant with their environment. Occupant's needs can be (i) physical or (ii) non-physical (Figure 4)

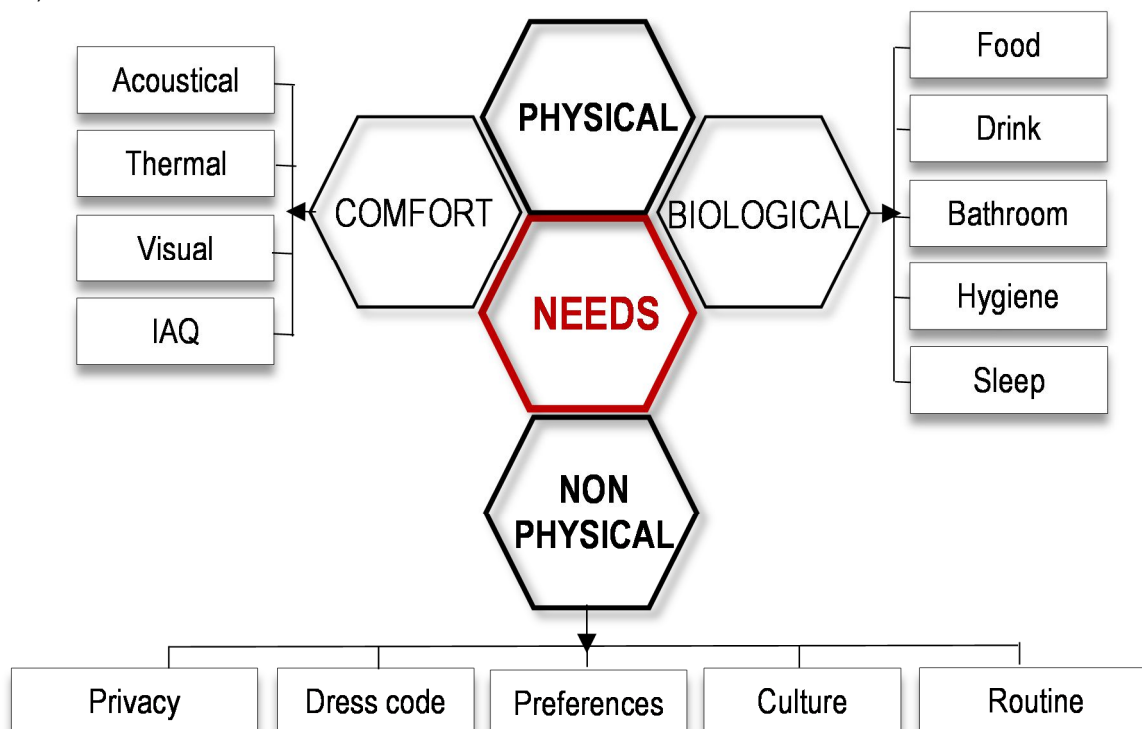


Figure 4. The NEEDS component of the DNAS behavioral framework (Hong, D'Oca et al. 2015)

Both of these aspects need to take into account. On the one hand they contribute to the overall satisfaction of the occupant. On the other hand, they impact building energy performance by influencing occupant interaction with building systems.

- i. Physical needs include aspects of occupant's comfort with the indoor environment, which is a combination of acoustical, thermal, visual and IAQ requirements, as well as satisfaction of some biological needs.
- ii. Non-physical needs include factors such as the need for privacy or the need to maintain outside views.

Actions

Actions are the interactions with systems or activities that an occupant can conduct to achieve environmental comfort. Actions connect occupants' inside-world needs with the environmental outside world. Action is triggered by Humphrey's principle for adaptive behavior stating that – “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Humphreys and Nicol 1998). The actions may be an interaction with a system control or building component, which the occupant believe might relieve his/her discomfort condition. Occupants might decide to move through spaces in order to meet different array of comfort (i.e. moving to a cooler area of the building), biological (i.e. taking lunch break or going to the toilet) or non-physical needs (i.e. attending a meeting). Actions can also include indirect measures to satisfying some previously mentioned needs, such as reporting discomfort to a building manager. The framework structure also allows to report the possibility for inaction, when the occupant decides to do nothing but to suffer the discomfort (Figure 5).

Example of the DNAs concept, considering the simple scenario of an occupant working inside a naturally ventilated office with operable windows during the summer is provided in Hong, D'Oca et al [Paper 6].

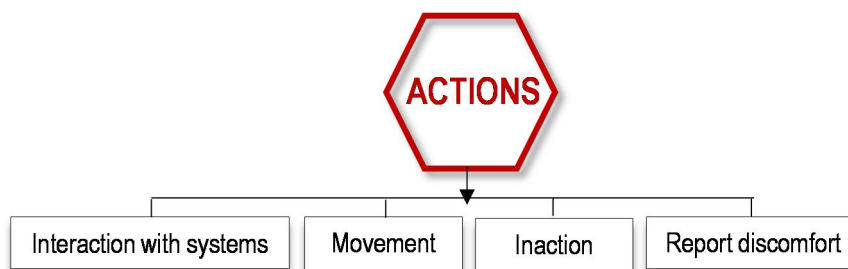


Figure 5. The ACTIONS component of the DNAs behavioral framework (Hong, D'Oca et al. 2015)

Systems

Systems refer to the equipment or mechanisms within the building outside world with which an occupant may interact to restore or maintain environmental comfort (Figure 6). Common systems that are subject to occupant control and actions include windows, window blinds/shades, lights, thermostats, space occupancy, and electrical equipment. The clothing worn by an occupant, or the interactions which prompt feedback energy from visualization systems, can also be considered a system in the framework.

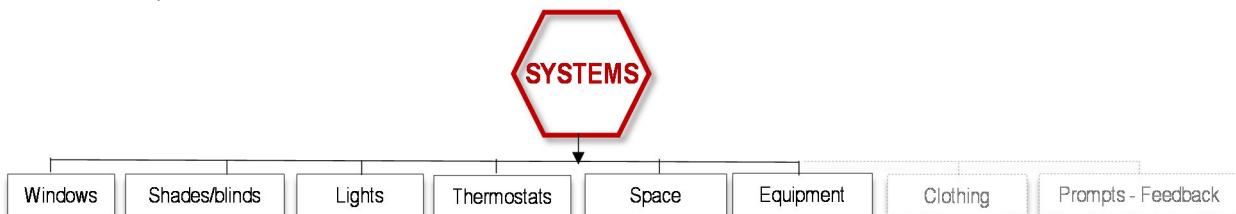


Figure 36. The SYSTEM component of the DNAs behavioral framework (Hong, D'Oca et al. 2015)

Further details of the DNAs framework can be found in Hong, D'Oca et al. [Paper 6].

More detailed analysis of constrains for application of the DNAs framework and insights into the obXML schema are provided in the following Section of the dissertation [Paper 7].

Paper 7

T. Hong, S. D'Oca et al.

An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema.

BUILDING AND ENVIRONMENT – 2015

A unifying format to express a wide variety of behavioral models is supposed to deliver a foremost optimization service to the building simulation community. Accordingly, the DNAS framework has been implemented into an XML (eXtensible Markup Language) schema, titled 'occupant behavior XML' (obXML) and published in Hong, D'Oca et al [Paper 7].

A number of data formats were considered appropriate for providing data structure to describe occupant behavior model input into BEMs. With respect to the implementation of the DNAS framework in a schema, we selected the XML (eXtensible Markup Language) as the most appropriate for the purpose of behavioral data standardization in building energy simulation. Originally designed to meet the challenges of large scale electronic publishing, in its general form, the XML is a meta-markup language providing a standard data format for representing structured information (Fourer et al. 2009).

Typically, XML files take form of human and machine readable documents conveying transferability characteristics among i) applications of the same software and ii) between different software tools. Similar to other markup languages such as HTML, XML (eXtensible Markup Language) uses tags to separate data items from one another. Tags are nested in a tree structure, but the definition, position and order of tags is left to the user and can be described in a schema file (which is itself an XML document). One of the advantages of working in XML is the existence of tools such as parsers, visualization tools, development environments, etc.

The basic unit of an XML files is a portion of code enclosing both the content and the markup of the data. While the content conveys the actual data information – i.e. time of the day – the markup elucidates the content of the information – i.e. noon. More generally, markups render attributes, values, tags and ranges of the corresponding data content. As an example, the aforementioned instance is described in an XML language in a form:

```
<timeofday=noon>
```

Well-formed XML language follows some basic standardized syntax rules.

- The XML language is case sensitive
- No spaces are allowed between content and markup
- The attribute values must appear in a "value" format

The XML language has the great advantage to be a neutral exchange language able to represent data and models in such a way, which can be easily integrated in diverse software environment.

The obXML schema is used for the practical implementation of the DNAS framework into building simulation tools. The obXML schema has inherent flexibility to represent numerous, diverse and complex types of occupant behaviors in buildings, and it can also be expanded to encompass new types of behaviors. The implementation of the DNAS framework into the obXML schema aims to facilitate interoperability between occupant behavior models and building energy modeling programs. The obXML schema allows relationships to be formed and defined between different drivers and the eventual action, in a standardized way. The obXML schema generates XML data structured occupant behavior models to be co-simulated with the Energy Plus into a functional mockup unit (obFMU). The obXML schema is designed to provide enough flexibility for existing and future occupant behavior to be captured and implemented into building energy models in a consistent way.

The topology of the DNAS framework implemented in the obXML schema implies a tree-diagram schema structure. The obXML has a main root element OccupantBehavior, linking three main elements representing Buildings, Occupants and Behaviors (Figures 1, 2, 3).

Detailed description of the obXML topology tree-like structure is described in more detail in Hong, D'Oca et al. Moreover, as illustrative example of behavioral models using the obXML framework, a Weibull distribution and logistic regression equation are implemented into the obXML schema and presented in Hong, D'Oca et al. The framework flexibility allows other human-building interactions (e.g. thermostat, equipment, lights interactions, or occupant movement) to be implemented using a similar methodology.

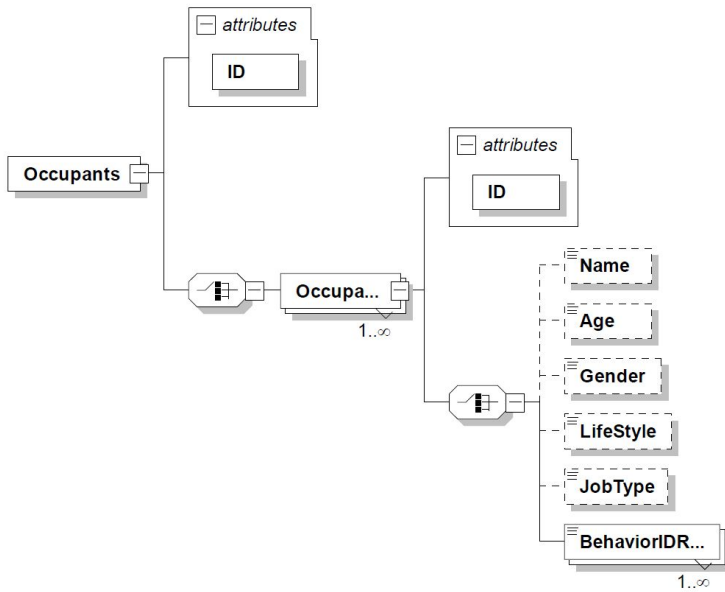


Figure 1: The tree diagram identifying the input characteristics of the occupant(s) (Hong, D'Oca et al. 2015)

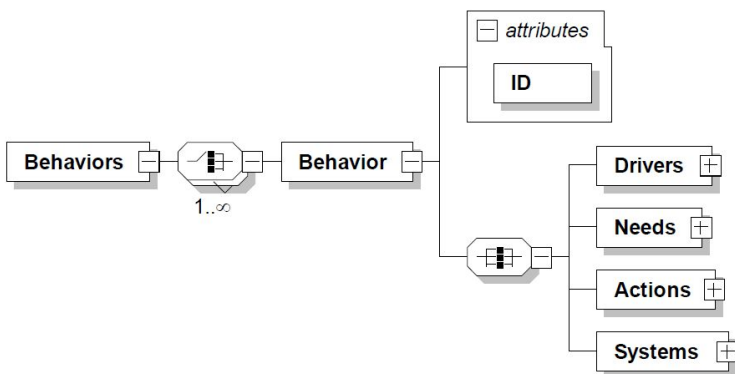


Figure 2: The topology of the behavior element showing the general characteristics of how behavior is branched into drivers (Hong, D'Oca et al. 2015).

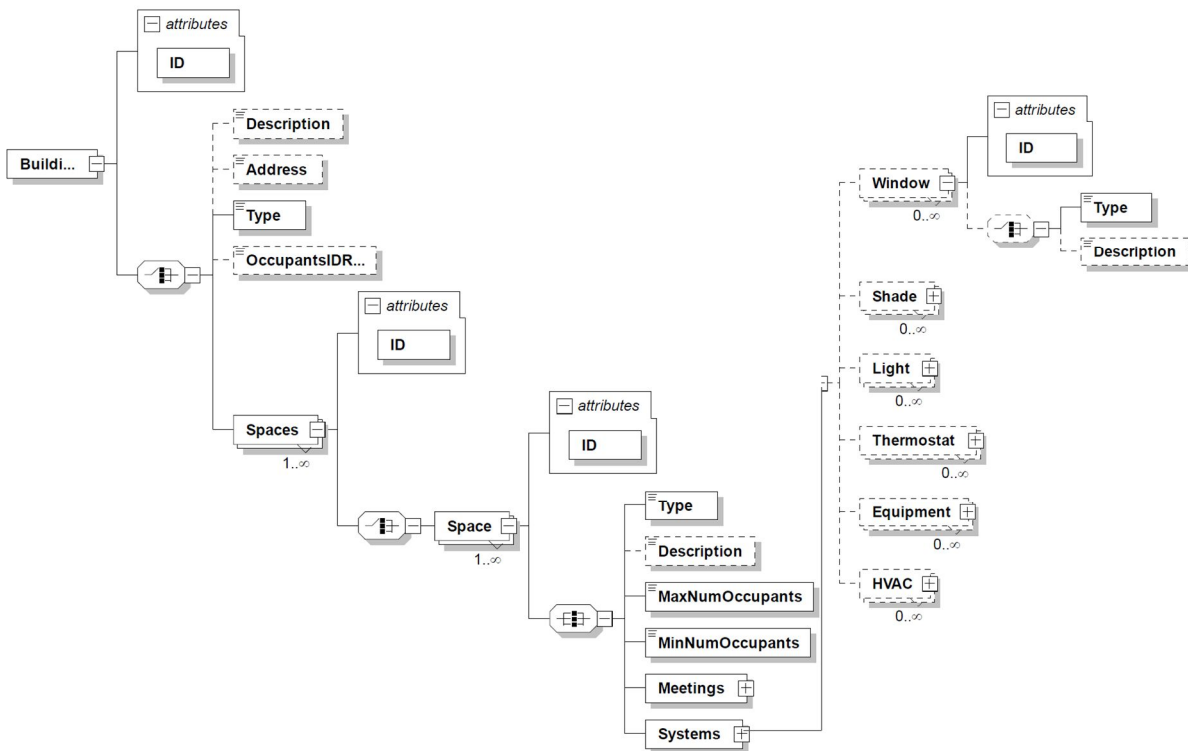


Figure 3: The tree diagram showing the general characteristics of the building, space and systems, including the details of the window, shade, light, thermostat, equipment and HVAC systems having an ID, type and description (Hong, D'Oca et al. 2015).

Outcome: a standardization ontology and syntax for representation of energy-related occupant behavioral models in building simulation tools.

The obXMLschema is designed to provide enough flexibility for both existing and future occupant behavior, building energy and system models to be captured in a consistent way. The obXML schema follows extensible design criteria to provide a wide range of stakeholders (researchers, designers, energy modelers, building engineers etc.) with a new tool to standardize the representation of energy-related occupant behavior in buildings, and quantify the impact on building operations, technology and system performance, as well as design and retrofit strategies.

Efforts are in force to build an obXML library, translating the existing occupant behavior models published over the last 30 years in international journals into the XML formal language. When decoded into the obXML semantic, OB models developed for one tool and application can be used for any other tools applications. When implanted into the obFMU logic, any obXML translated model can be co-simulated with Energy Plus, via a Functional Mockup Interface (FMI) (Blochwitz et al. 2009) such as Modelica (Wetter 2011; Noudui et al. 2014), enabling model validation and outcome comparison.

Further details of the obXML schema can be found in Hong, D'Oca et al. [Paper 7].



GAP BETWEEN PREDICTED AND ACTUAL BUILDING ENERGY CONSUMPTION

IS THERE SUFFICIENT BENEFIT IN QUANTIFYING OB IN BUILDING ENERGY SIMULATIONS?

- PAPER 8 ● **S. D'Oca**, S.P. Corgnati et al.
Effect of thermostat and window opening occupant behavior models on energy use in homes
BUILDING SIMULATION – 2014
- PAPER 9 ● **S. D'Oca**, S.P. Corgnati, et al.
Insights into the variability of energy consumption due to adaptive occupant behaviors in offices.
Submitted BUILDING SIMULATION – 2016

4.4 OB Simulation

“Man is a slow, sloppy, and brilliant thinker; computers are fast, accurate, and stupid.”
 – John Pfeiffer

State of the art limit of research	Unabridged research questions	Innovations	Outcomes	Field Research of
Gap between predicted and actual building energy consumption due to a lack of adequate behavioral inputs in building energy simulation	Is there sufficient benefit in quantifying OB in building energy simulations?	Occupant behavior simulation in BEMs	Simulation studies of energy-related occupant behavior in residential and commercial buildings	OB Simulation

Typically, adaptive energy-related behaviors in buildings - operating windows, blinds, and lights, and adjusting thermostats, – have been modeled in energy simulation tools by means of predefined rules and fixed schedules. When implemented in simulation tools, advanced behavioral models defined by means statistical analysis or real building operational data correlated to indoor and outdoor environmental triggers generate great variation with respect to deterministic simulation. Whether this variation can be assumed as an improvement in accuracy of building performance prediction is still an open question. Simulations results need to be validated against measurements of actual energy consumption.

To this extent, a simulation study (Smires et al. 2012) explored the potential benefit of implementing a stochastic model of a window opening behavior (Rijal et al. 2008) against traditional deterministic models. Outcomes of the simulation implementing the stochastic window opening model and deterministic ones were compared against measured window state data in a real building. Results of the study demonstrated the specific stochastic model was unable to replicate building specific patterns of window opening behaviors (i.e. several windows were found to be completely unused throughout the measured period over a broad range of internal temperatures). Interestingly, the simplified model resulted in higher correlation ($R^2=0.70$) values than the truly stochastic model and its derivate ($R^2=0.54$). This observation interestingly questions the predictive capacity of actual modeling approaches and their applicability to a broader audience. **Hence, the question if there is sufficient benefit in simulating stochastic models of occupant behaviors in building is conversed in this dissertation.**

Innovation: Occupant behavior simulation in BEMs

Two simulation studies, one for a residential building and one for an office building, implementing OB advanced models in BEM simulation tool (IDA ICE), are proposed to support discussion around the topic

Several adaptive occupant behavioral models based on field measurements in real buildings have been implemented into IDA ICE. Thanks to its extensible equation-based modeling nature, which makes it straight-forward to quickly expand the software controls with external models, probabilistic equations describing users' interference with various type of controls can be implemented at the advanced level.

Results of such advanced simulations have been broadly published in literature (Gunay et al. 2015). All these studies demonstrated implementation of stochastic user-driven adaptive controls – such as window opening, thermostat adjustments, blind usage - typically led to higher energy consumption when compared to simulations ran in accordance with fixed schedules based on minimum standard requirements and thresholds. Two simulation studies have been developed in the context of the PhD research, which are constructed on the same probabilistic simulation approach in IDA ICE.

This advanced simulation approach is based on a user customize code implemented as user function in can be explained as composed in three main steps, as follows:

- I. Implementation of probabilistic models of occupant behavior (based on statistical analysis of monitored building and humans energy behaviors) written as a NMF language as inputs in the dynamic energy simulation program.
- II. Run of a set of probabilistic simulations
- III. Comparison of the energy consumption resulting from average of probabilistic simulation results, with outcomes of simulations adopting deterministic behavioral input values, and evaluation of the variation in simulated results.

The variation in simulated results is assumed as proxy for the impact of diverse profiles of occupant behaviors on the building energy consumption. Implicitly, this variation entails the concept that occupant behavior must be regarded as one of the key parameters causing discrepancies between predicted and actual energy performance (energy consumption and comfort level) in buildings.

Deterministic behavioral input in IDA ICE

Table 1 shows an example of how deterministic behavioral inputs are handled to model window operation for natural ventilation in IDA ICE. With respect to natural ventilation, standard schedules plus PI (Proportional-Integral) control assumes occupants to open windows if the indoor temperature exceeded a certain value ($25^{\circ}\text{C} \pm 2^{\circ}\text{C}$) and the outdoor temperature was lower than the indoor temperature. Such standardized behavioral control input is described as in D'Oca et al (D'Oca, Fabi, et al. 2014).

Table 1. Example IDA ICE deterministic input for opening windows using schedules (D'Oca et al, submitted)

```
((OPNCTRL :N "Window1" :T WINDOW :D "Window")
(:PAR :N X :V 0.5)
(:PAR :N Y :V 0.25)
(:PAR :N DX :V 4)
(:PAR :N DY :V 3)
(:PAR :N OPENING-CONTROL :V PI-CONTROL+SCHEDULE)
(:RES :N OPENING-SCHEDULE :V "Schedule people ORB")))
```

User custom code, user function

In order to implement behavioral models into IDA ICE, mathematical equations described in terms of NMF formal language, need to be converted into deterministic signals for the different system controls. Accordingly, the calculated probabilities are compared to a random number changing dynamically every five minutes. Within this time frame, if the simulated probability is higher than the random number, the adaptive action would occur. Then, the control action would not change until a new probability of change happens to be higher than the matching random number. Hence, by switching the random number list in the simulation program over a series of time, a probabilistic distribution of energy consumption of the building models is simulated.

Table 2 shows a user custom code, written in the NMF native input language, to simulate a probabilistic behavioral model in IDA ICE. The example relies on the probability function described in Andersen et al (Andersen et al. 2013). A multivariate logistic regression with interactions between influencing variables was used to infer the probability of a window opening and closing event.

Table 2. Example IDA ICE User Code for opening windows (D'Oca et al, submitted)

```

CONTINUOUS_MODEL Logistic
ABSTRACT
"Logistic regression.  $p = \exp(a+bx_1+cx_2+\dots)/(1+\exp(a+bx_1+cx_2+\dots))$ 
where a is the offset, b,c ... are coefficients and
x1, x2, ... are variables/insignals
Sends result to multiple output links"

/* Updates: 110921 rka, bounds added to denominator, OutSignal and polyn */
EQUATIONS
  polyn := SUM i = 1, n_in
    InSignal[i]* Coeff[i]
  END_SUM + OffSet;

  polynom := IF polyn > 700 THEN
    700
  ELSE
    polyn
  END_IF;

  denominator := IF 1+EXP(polynom) < 0.00001 THEN
    IF 1+EXP(polynom) > -0.00001 THEN
      0.00001
    ELSE
      1+EXP(polynom)
    END_IF
  ELSE
    1+EXP(polynom)
  END_IF;

  OutSignal = IF EXP(polynom)/(denominator)<0 THEN
    0
  ELSE
    IF EXP(polynom)/(denominator)>1 THEN
      1
    ELSE
      EXP(polynom)/(denominator)
    END_IF
  END_IF;
LINKS
  FOR i = 1, n_in
    GENERIC InSignalLink[i] InSignal[i] (input) "Input signals"
  END_FOR;

  GENERIC OutSignalLink OutSignal (output) "Output signal";
  GENERIC OffsetLink Offset (input) "Intercept";

  FOR i = 1, n_in
    GENERIC CoeffLink[i] Coeff[i] (input) "Coefficients"
  END_FOR;
VARIABLES
  GENERIC OutSignal OUT "Output signal"
  GENERIC InSignal[n_in] IN "Input signals/Variables"
  GENERIC polyn LOC "Sum inside the parenthesis"
  GENERIC Coeff[n_in] IN "coefficients"
  GENERIC OffSet IN "Intercept"
  GENERIC denominator LOC "denominator - can not become 0"
  GENERIC polynom LOC "bounded polyn"

/*PARAMETERS
type name role def min max description */
MODEL_PARAMETERS
  INT n_in SMP 2 0 BIGINT "Number of InSignal links"

/*EXTENSIONS
  ALGORITHMIC_NAME AdderLogistic;
END_EXTENSIONS*/
END_MODEL

```


Paper 8**S. D'Oca, S.P. Corgnati et al.**

Effect of thermostat and window opening occupant behavior models on energy use in homes

BUILDING SIMULATION – 2014

Results from early studies (Andersen et al. 2013; Fabi et al. 2012) highlighted the influence of occupant's behavior on the building energy demands is rising to 36% in comparison to the buildings where the occupants' interaction with the controls is regulated by fixed schedules. In these studies, multiple behaviors are simulated simultaneously, impeding isolating the intrinsic influence of a particular adaptive behavior individually, but also yielding to a smaller energy impact than each behavior might allocate on its own. The research presented in this Ph.D. study is an extension these previous probabilistic simulation approaches. A new study hence implemented both window opening and heating control probabilistic models into a single building energy model – by using the dynamic simulation software IDA ICE.

To replicate probabilistic control actions of a window opening and thermostat set-point, logistic regression formulas were implemented in the dynamic building simulation software IDA Ice. These formulas describe a relationship between the change in window or thermostat state and a set of independent predictors used when the outcome is binary, that is when there are only two possible accounts (0 or 1) in the case:

- open/not open windows – turn up/not turn up thermostats;
- close/not close windows – turn down/not turn down thermostats.

The outcomes of the models were probabilities of an action occurring (windows open/close heating set-point increase/decrease) within the next 10 minutes (since the independent variables were measured at 10-minute intervals). To determine the state of the windows and heating set-point, the probabilities were compared to a random number that was generated at 10-minute intervals. An action occurred in the simulation if the calculated probability was higher than the random number. The window would stay open, or the thermostat would stay turned up until the likelihood of closing the window or turning down the thermostat was higher than the matching random number. Window sensor recorded a binary state of a window being open or closed, no information about window tilting angle was available. For this reason, the opening signal in the simulation model was multiplied by a fixed degree of opening of 20%. Each model was run ten times. Since window openings and heating set points were modeled stochastically, the ten simulations did not have identical results. The mean value of a probabilistic distribution of results (fluctuation of 10 simulations) instead of single deterministic value was considered as more representative of actual energy consumption.

In the simulation phase, for every model we simulated a set of 10, 20 and 30 runs, to highlight the oscillation among results distribution. No evident benefits emerged in running each model more than 10 times since (a) small variation (from 10% to 12%) among results distribution was found between the sets of 10, 20 or 30 runs and (b) one IDA Ice yearly simulation implementing probabilistic inputs for window and thermostat operation lasted up to 2 hours. To highlight the magnitude of occupant behavior influence on energy consumption, simulations were performed for three different climate locations: Mediterranean (Athens), Continental (Frankfurt) and Nordic (Stockholm) climate. Additionally, with the aim to investigate the influence of thermal comfort and air quality perception on occupant behavior, simulations were performed for the three comfort category conditions (Categories I, II, III) as defined in Standard EN 15251:2006 both for heating set-point acceptability (21°, 20°, 18°) and for ventilation rate values (0.49 L/(s·m²), 0.42 L/(s·m²), 0.35 L/(s·m²)).

Firstly, the study simulated energy performance as generally performed in the design stage of typical building energy model simulations, by using deterministic inputs of occupant behavior for air change rate and thermostat set points.

Secondly, a model considering the probabilistic interaction of window openings was implemented, while the control of heating set-point was still considered as deterministic input value dependent on the comfort category.

Thirdly, both window opening and closing and heating set-point adjustments were described through probabilistic models as logistic regression functions. The probability of opening and closing windows was inferred for a behavioral model,

regarding naturally ventilated dwellings by using variables and coefficients statistically treated (Fabi et al. 2012). A probabilistic control of thermostats was added to the previous model whereby variables and coefficients statistically treated have been used (Andersen et al. 2011).

Finally, probabilistic behavioral inputs were described as functions of interactive behavioral patterns representing “active”, “medium” and “passive” operation on the window and thermostat control systems (Fabi et al. 2012). Each of three behavioral models implementing window controls was matched in a macro with the three concerning thermostat adjustments. Accordingly, nine models were implemented, covering all possible combinations between them.

Results of the research focused on differences in delivered heat energy consumption between singular values of deterministic simulations and mean values of probabilistic simulations. This simulation study demonstrated the usage of probabilistic methods to investigate window positioning and temperature set-point adjustments in buildings – rather than simulations making usage of deterministic values suggested by UNI Standard EN15251 – lead to a variation to energy consumption prediction up to 60% in the extreme case (Figure 20).

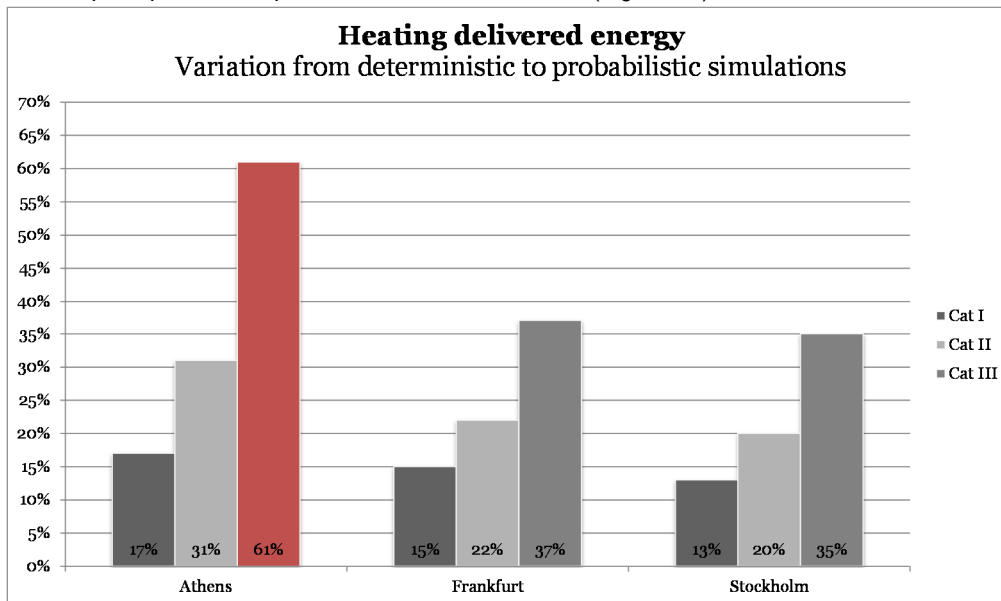


Figure 1: Variation in simulated heating delivered energy for three climate locations and comfort categories (Cat I-II-III UNI Standard EN15251) (D’Oca et al, 2014)

Despite this initial study uncovered some unexplored fields in simultaneously implementing user-customized codes in IDA ICE, and occupant behavioral patterns virtualization in building simulation tools, some simplification in method application still existed. Specifically, window opening and heating behaviors were individually triggered by environmental and contextual parameters. However, any explicit logic referring to the order of interactions was implemented into the simulator. More insights on preferences and triggers leading occupants to opt out for specific adaptive opportunities better than others need to be uncovered and applied to behavioral models implemented into building simulation tools.

Results of this research gave confirmation to the hypothesis that occupants’ behavior in buildings is to be regarded one of the key reasons for discrepancies between predicted and actual energy consumption in dwellings. Some building occupants are very much aware of their energy bills (heating and electricity) and tend to act in ways to reduce their bill rather than to maintain a high level of comfort. In contrast, energy-unconscious occupants liberally interact with the control system to improve comfort conditions in their homes.

Findings of this research underlined that occupants’ interactions within building envelope and control systems are strictly interrelated to the pursuit of personal comfort, the perceived indoor environmental quality and therefore global energy performance of the buildings (Paciuk, 1990)

More detailed outcomes and discussion of the proposed simulation study are presented in D’Oca et al. [Paper 8].

Paper 9

S. D'Oca, Corgnati et al.

Insights into the variability of energy consumption due to adaptive occupant behaviors in offices

Submitted – May 2016

In this study, a reference office building representative of the European building stock is simulated in two climate location (Mediterranean and Continental), having two typical building envelope configurations, light, and massive envelope. The simulation models aim to test the robustness of different building envelope design and climate conditions on some adaptive occupant behaviors in office buildings. Four probabilistic models of adaptive occupant behavior selected from recently published literature, concerning (Figure 1):

- 1) Window opening (Haldi & Robinson 2009)
- 2) Blind usage: Haldi and Robinson (Haldi & Robinson 2010)
- 3) Heaters, fans (Nicol 2001)
- 4) Artificial lighting turning on/off: Nicol et al. (Nicol 2001)



DETERMINISTIC MODELS

Operation on windows
not allowed.
Fixed air change rate of 0.5 ACH every hour is assumed provided by wind dependent infiltration

External shadings
no user control: never drawn

Heating/Cooling set-point
of 21°C and of 25°C (±2°)
Heating and cooling season are differently based on climate location, following the occupancy schedule

Artificial lighting
10 W/m² of internal gains, following the occupancy schedule, with no link between operations and luminance.

STOCHASTIC MODELS

Haldi and Robinson, 2008
Logistic regression function for actions on:
Opening probability
• T_{int} , T_{out} , $Rain$ (event), prior absence duration
Closing probability
• T_{int} , T_{out}

during
1. arrival
2. departure
3. during occupancy

Haldi and Robinson, 2009

Nicol, 2001

Nicol, 2001

$$\ln\left(\frac{p}{1-p}\right) = a + b \cdot T_{out}$$

Figure 1: Selected behavioral models for the adaptive opportunities simulated in the building energy model (D'Oca et al, submitted)

By isolating other paramount influencing factors on energy consumption, such as building morphology, orientation, and plant system type, a comparative analysis of the energy simulation results is performed to provide insights into the variance of building energy performance due to individual adaptive occupant energy-related behaviors. Synthetic variability indicators are proposed to measure the impact of the selected energy-related occupant behaviors on heating, cooling and electricity energy consumption and robustness with respect to dissimilar building envelope configurations and climate conditions. Implementation of the four probabilistic models of adaptive occupant behaviors into the BSP allowed isolating – by means a comparative analysis with deterministic simulation results – a global variability indicator of the simulated delivered energy due to adaptive occupant behaviors of 22% (Figure 2).

Behavioral adjustments in the indoor environment were responsible for a twofold variation effect compared to standardized simulated energy performance. On the one hand, a reduction of energy use for dynamically managing the solar heat gains entering the building is observed – with particular regards to usage of window blinds. On the other hand, increments for the usage of air conditioning (heating and cooling) and natural ventilation emerged in every climate condition and for both building envelope configurations.

VARIATION OF BUILDING CONSUMPTION DUE TO OCCUPANT BEHAVIOR

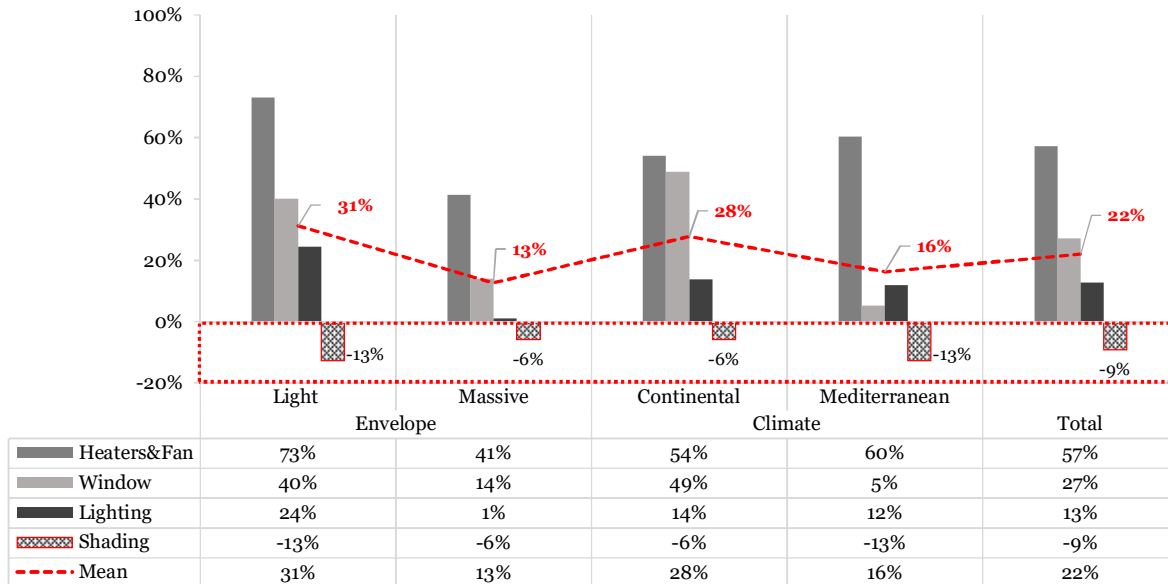


Figure 2: Variability indicators of building energy consumption due to specific occupant adaptive behaviors simulated by means behavioral models in IDA ICE (D'Oca et al, submitted)

Massive buildings located in continental climates emerged as the most robust building configuration concerning adaptive occupant behavior. In opposition, light envelope buildings located in continental climates appeared more affected by the occupant driven adaptive operation of building controls. The presented results suggest the design of manual control of environmental conditions and adaptive opportunities can profit from the robustness of building design such as thermal inertia as well from mild weather and narrower thermal excursions. Conversely, light envelope characteristics and more severe climatic conditions have been demonstrated to be factors associated with buildings, which are more susceptible to occupant's interaction with control systems. In this view, outcomes of this study are aiming to support building designers, architects and engineers, to design building that are –on the one hand – less sensitive to occupant adaptive behaviors when simulated stochastic controls are indicating uncertainty in energy consumption variation, and to profit – on the other hand – from the energy reduction potential of environmental adaptation mechanisms. An extensive presentation of the simulation is proposed as in D'Oca et al. [Paper 9].



LACK OF EFFECTIVE SOLUTIONS AND INSIGHTS TO LEVERAGE ENERGY SAVING POTENTIAL OF OB

HOW TO ENGAGE OB INTO OPTIMIZED CONTROL FORMULATION IN BUILDINGS?

- PAPER 10 ● **S. D'Oca**, S.P. Corgnati et al.
Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings. ENERGY RESEARCH & SOCIAL SCIENCE – 2014
- PAPER 11 ● **S. D'Oca**, S.P. Corgnati et al.
Introduction to an occupant behavior motivation survey framework.
Proceeding of Clima2016 Conference – Aalborg, Denmark 2016

4.5 OB Engaging

Buildings do not use energy: people do.

– K.B Janda

State of the art limit of research	Unabridged research questions	Innovations	Outcomes	Field Research of
Lack of effective solutions and insights to leverage energy saving potential of the human factor in building energy usage	How to engage effectively the human operator into optimized control formulation in buildings?	Translating data, models and simulations into behavioral insights and smart controls	Effective energy-saving solutions engaging human in the loop of building and data systems	OB Engaging

Behavioral change measures in buildings have been recognized as a low-cost, high-impact way of reducing building energy consumption and operation costs. These behavior changes have been shown to reduce building energy consumption to a similar extent as technological innovation investment for energy efficiency measures. The information collected for 3 years of study in this field suggests that with an investment of between 1-2% of energy spends in efficient user engagement campaigns, energy costs can be cut up to 30% in office buildings (Hong 2012), and on average around 15% in residential buildings (D'Oca et al. 2014). Yet, very few campaigns and implementation of human-centered control logics can demonstrate the long-term perseverance needed to achieve results. However, how to effectively engage the human operator into optimized control formulation in buildings is still an open question.

Effective behavioral programs need to bring together technical expertise on technology innovation at the ICT and building level (monitoring, sensing and data processing and visualization) and increased understanding of behavioral psychology, sociology, as well as consumer marketing expertise. Despite the review of current studies and programs, there is no existing one-size-fits-all solution to address the topic. Only a few design principles that reinforce all successful behavioral change programs exists. Accordingly, this dissertation focuses on a twofold approach to providing solutions to engage occupants in residential and office buildings towards energy-savings and enhancement of energy efficiency.

Over the last 30 years, focused attention has been given on the topic of energy consumption in households. On the one hand, residential consumption appears responsible for major detriments in the building sector leading to Co2 emission worldwide (Poortinga et al. 2003). On the other hand, results of a study of the European Environmental Agency (EEA 2013) underlined that the energy saving potential of improving energy consumption patterns in homes can range from 2 to 20%. This interval spans from indirect feedback - e.g. enhanced billing – (2–10%) and direct feedback and target settings – e.g. including smart meters data (5-15%) to energy audits, community-based initiatives and combination interventions (5-20%)

Innovation: Techniques for translating data into behavioral insights in homes

With the aim of reducing energy consumption patterns in the residential sector, two general routes to pursue were proposed (Wood & Newborough 2003), which include the human factor in energy use:

- 1) achieving widespread usage of low-energy domestic equipment (technical approach);
- 2) promoting “socio-technical” behavioral programs among householders.

Another possibility (Ueno et al. 2003) to induce energy saving potential by providing household members with:

- 3) persuasive information on actual domestic energy consumption.

The first technical route requires a medium capital intensive investment (buying and substituting old and inefficient equipment with more efficient ones), and results are achievable in a relatively short term (immediate reduction in consumption due to the technical enhancement). Researchers (Kowsari & Zerriffi 2011; Morton & Griffiths, 2012) suggest the increase in the availability of new energy-efficient technologies might ultimately engender an increase in household energy consumption. Phenomena such as the rebound effect may occur, (Oikonomou et al. 2009; Steg & Vlek 2009), in which the increasing use of energy-efficient equipment may directly result in increased energy use, are playing a part of this unachieved goal. Moreover, due to technological limitations in a further reduction in energy consumption, nowadays office equipment, and domestic appliances have reached an asymptote in the enhancement of energy efficiency.

The second socio-technical route encompasses promoting “energy-conscious” behavior by requiring low capital intensive investments (Han Q. et al, 2013). These are typically referring to the financial investments to support the behavioral change program, such as monetary incentives, costs of intervention strategies or small technical infrastructure.

Energy consumers appear to modify their behaviors positively when motivated by financial incentives (Gadenne et al. 2011; Whitmarsh et al. 2011). A study conducted among several EU countries confirm (Mills & Schleich 2012) the highest rates of energy savings were motivated mainly by financial drivers, compared to a low percentage attributed to environmentally sensitivity determinations. For this reason, the energy providers and utility programs are most commonly developing engagement strategies leveraging on financial incentives to influence individual energy use.

A third route to induce energy saving potential in households is defined by sociological approaches (Sovacool et al. 2015). Successful behavioral campaigns in the residential sector emphasize a perspective, which interrelates personal, social and technical aspects as a whole of a wider consumption structures (Hobson 2003; Nye et al. 2010). About the connection between the individual and collective sphere of behavior, people tend to be concerned about their positive image, and individuals are encouraged to follow the norms of a group to which they intend to belong. Significantly, behavioral campaigns based on peer comparison strategies to foster energy consumption reduction at the household level (such as Opower) not only present demonstrated results (2% on average); also, achieved behavioral changes appear to be stable over time and geographical region. Such outcomes point out the importance of social influence towards positive energy-saving behaviors as well as the high dependency of behavioral change processes to the sphere of social norms. However, at the actual state, the energy-saving effectiveness of such measures cannot be assured a priori (Gadenne et al. 2011).

Paper 10

S. D'Oca, S.P. Corgnati, et al.

Smart meters and energy savings in Italy: Determining the effectiveness of persuasive communication in dwellings
ENERGY RESEARCH & SOCIAL SCIENCE – 2014

As part of this Ph.D. research, the effectiveness of a monitoring system including several devices involved in the residential energy management in reducing energy consumption was tested (Energy@home 2014). The system's general architecture is reported in Figure 1 and further described as in D'Oca et al [Paper 11]. In the home domain, several actors that refer to two separated but linked home network – the Home Area Network and the Home Network – can cooperate through communication protocols (ZigBee and Wi-Fi).



Figure 1. The system's general architecture of the Energy@home system (energy@home.it)

Gathering data by smart meters and appliances

The smart monitoring system has been tested by a selection of 31 householders, designated among volunteers all over Italy. Employing the Electronic Meter and the Smart Appliances and Plugs, general electricity loads and individual devices' electric consumption were recorded with a two-minute time-step. To create a comparable set of data, users were clustered into a "family type", organized accordingly to household composition information gathered via a web questionnaire.

Gathering data by the on-line questionnaire

A web questionnaire was deployed and sent to users, to get useful information on family types. Volunteers were asked about information on household composition, family habits, and some electricity equipment home installed. Information was gathered using a web questionnaire created using the Google Form open tool and sent to users by e-mail. The questionnaire included straightforward and non-intrusive short questions, mainly listed below:

- Geographical location of the dwellings
- House information, such as building type, orientation, size, age of construction, state of maintenance
- Domestic household information, such as number and age of family households, level of education, activity and unoccupied periods
- Appliances usage information, such as number and kind of owned appliances, time, and periods of usage.

Developing Energy Behavior Key Performance Indicators (KPIs)

An energy behavior key performance indicator is a type of energy efficiency measurement. It is a functional tool for energy users as well as utilities and policy makers to making progress toward strategic goals and for the identification of potential improvements in users' energy behavior. The aim of the research was to provide users with energy behavior KPIs that mainly identify a set of useful values, indicators and information in a persuasive way. A wide range of KPIs were established in this project, listed as follows:

- Quantitative KPIs: indicators that can be presented as a number (i.e. kWh/year; €/year)
- Qualitative KPIs: indicators that cannot be presented as a number (i.e. energy behavior profile)
- Process KPIs: indicators that represent the efficiency of the behavioral-awareness process (i.e. energy consumption reduction in %)

Quantitative KPIs

Quantitative KPIs are indicators that can be presented as a number, such as energy breakdowns, the energy or economic projection in kWh/year or €/year, based on the actual trends in consumption.

Annual electricity breakdown

For every user, an energy breakdown of the monitored electric load was performed (Figure 2).

The electric energy consumption monitored in every trial home (smart meter) was split into shares, corresponding to the electric load of the main electric equipment controlled by the E@H kit (TV, refrigerator, washing machine, dishwasher). A proportion of unplugged energy loads, derived by subtracting the electric energy consumption related to the monitored E@H kit (smart plugs and smart appliances) from the global smart meter, was also highlighted. This share is on the average around 40-50% of the domestic electric consumption and concerns electric loads for lighting, as well as widespread white goods (i.e. iron, vacuum cleaner, oven, microwave, PC, and any other kind of plug in general). The monitored annual electricity breakdown was hence compared to a national annual electricity breakdown benchmark (MICENE, 2014).

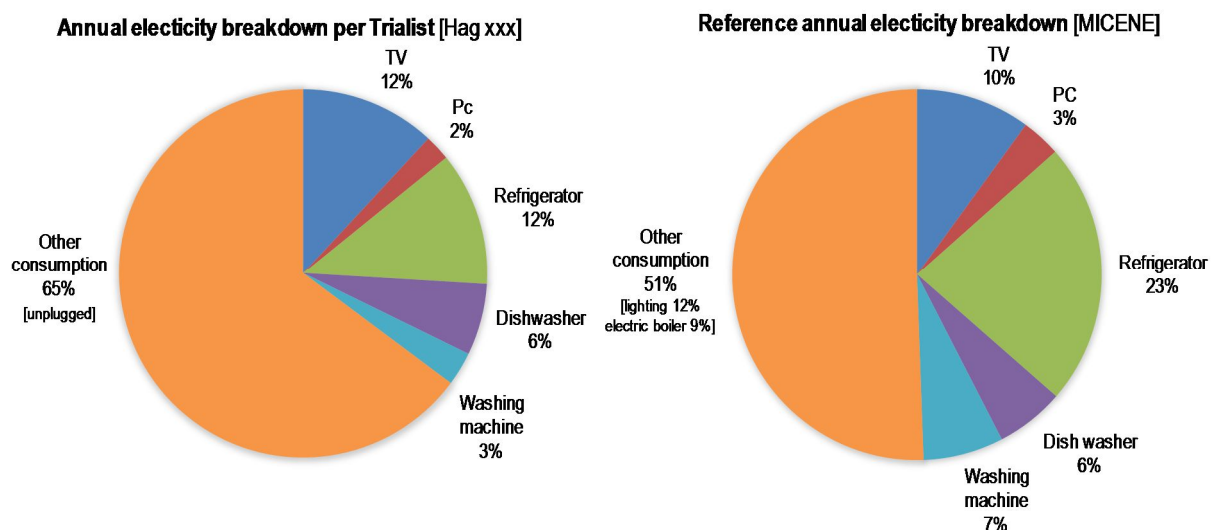


Figure 2. Monitored annual electricity breakdown, compared to the reference annual electricity breakdown (D'Oca et al, 2014)

Creation of reference benchmarks of typical electric consumption

Among the clustering methods, the comparison of the users' current electric consumption to reference values emerged to be effective to classify immediately "saver", "average" or "intensive" user profiles related to electric energy usage. Reference values (benchmarks) may be derived from existing studies providing national average values (vertical benchmarking), or from past energy consumption monitoring data (horizontal benchmarking) related to specific users' (family type) profiles, of the user itself. Reasonably, if benchmark setting were to be used, the boundary of the stated benchmark has to be carefully considered. Likewise for goals, if a target is too easy the effects could be limited while unrealistic goals can cause distress (Harkins and Lowe, 2000).

Useful vertical benchmarks related to typical domestic energy consumption in Italy are provided by the National Authority for electricity and gas energy consumption (AEEG, Autorità per l'Energia Elettrica e il Gas) and by the Italian National Institute of Statistics, ISTAT.

The creation of horizontal benchmarks for typical energy consumption of homogeneous groups of users (family type), reveals an adequate negotiation between the general and averaged benchmark value provided by national surveys, and the very specific one given by the monitoring of individual energy consumption pattern load. Moreover, even similar family types, both regarding buildings and households' characteristics, may behave following dissimilar trends, making the creation of coherent and efficient benchmarks unfeasible.

For every user, a projection of the electricity annual consumption, (Figure 3) the annual electricity bill, (Figure 4) as well the pro-capita consumption, (Figure 5) was compared with the one of similar households, as well as with the national typical average for domestic uses (2700 kWh/year corresponding to 516 €/year) accordingly to AEEG and for the per capita national annual average (1200 kWh/annual per capita) accordingly to ISTAT.

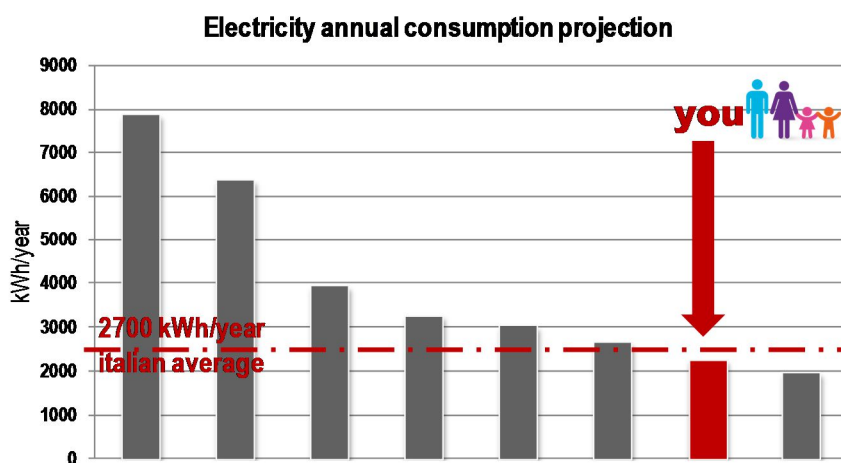


Figure 3

Electricity annual consumption projection with reference to a user having family composition of 4 households. Indication of similar households' energy consumption projection, as well as comparison with the national reference value (AEEG) (D'Oca et al, 2014)

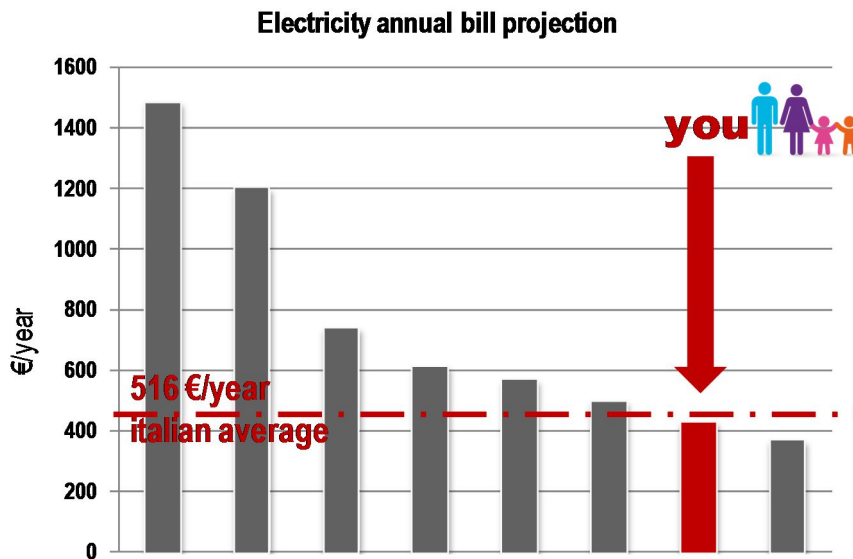


Figure 4
Electricity annual bill projection with reference to a user having family composition of 4 households. Indication of similar households' energy bill projection, as well as comparison with the national reference value (AEEG). (D'Oca et al, 2014)

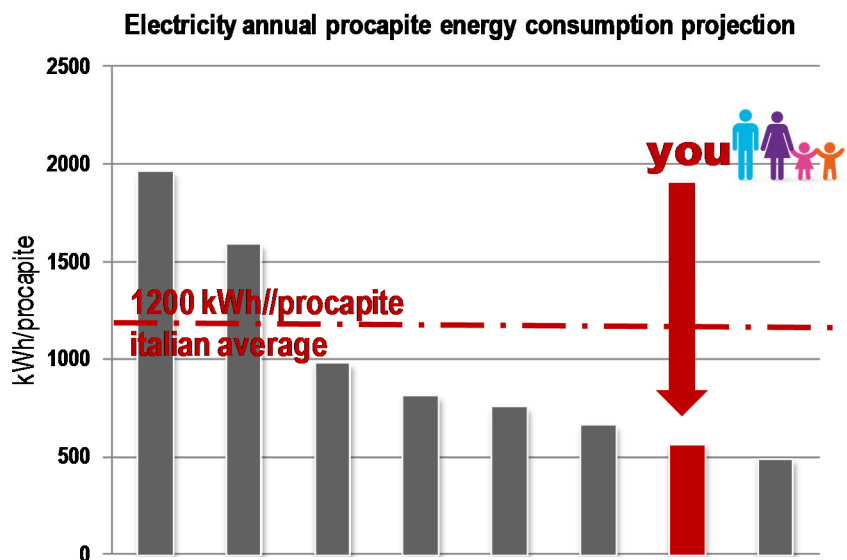


Figure 5
Electricity annual consumption projection per capita with reference to a user having family composition of 4 households. Indication of similar households' energy consumption projection, as well as comparison with the national reference value (ISTAT). (D'Oca et al, 2014)

For every monitored user, the electricity energy consumption was organized as a cumulative frequency, and a linear projection on a seasonal base was performed (Figure 6).

At the first stage, boundaries for “intensive”, “average” and “saving” profiles were indicated, concerning benchmark value provided by the Italian reference point (MICENE, 2014). A weekly energy consumption projection indicated, as the simple linear tendency, the possible amount of energy consumed (kWh/year) as well as the possible energy bill (€/year) at the end of the considered period.

A singular coefficient for electricity energy cost in Italy ($0,189 \text{ €/kWh}_e$)¹ was applied to define the annual energy bill projection. Figure 7 shows a projection of the amount of electricity the user will be using at the end of the season, if his/her consumption pattern would maintain stable over the considered time-frame. The projection is indicated in terms of energy cost (€) and energy profile (intensive, average, saving).

¹ Fixed rate for electric energy price accordingly to AEEG in 2013

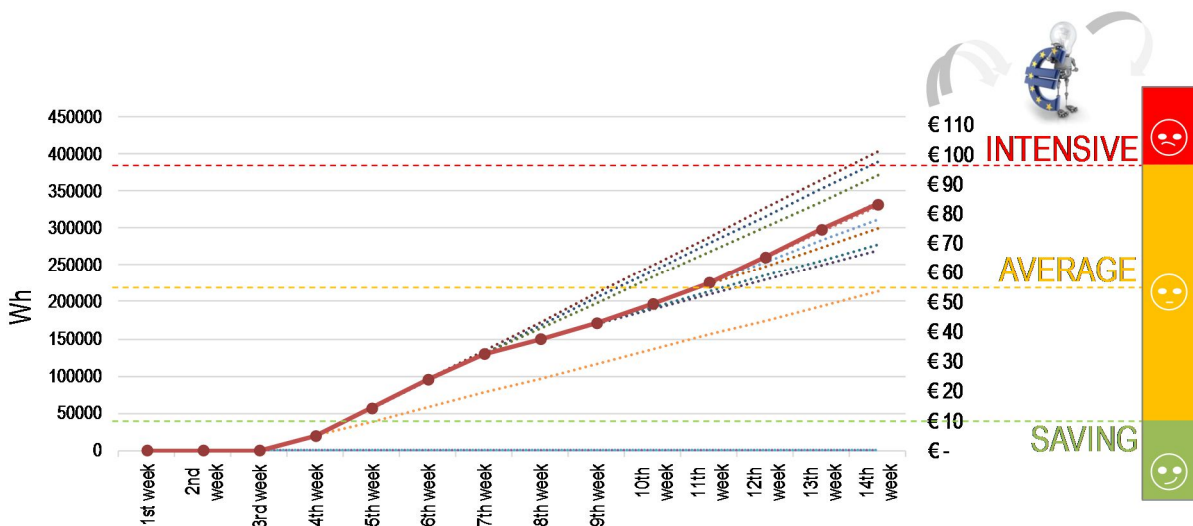


Figure 6. Quantitative KPIs. Projection for “intensive”, “average” and “saving” profiles, energy consumption and energy bill (D’Oca et al, 2014)

Qualitative KPIs

Qualitative KPIs are indicators that cannot be presented as a number, such as the behavioral energy profile of a user or a family type. Data was analyzed following a methodological approach explained hereafter, and the resulting energy behavioral profiles were used as horizontal benchmarks for each family type.

Representative electricity pattern loads were clustered for a set of users, to test the effectiveness of reducing energy consumption by providing them with tailored information regarding actual energy load in their homes, when compared to other similar users.

Pattern loads for family types may be further clustered based on number and age of the household members or family habits dependent on daily routine (number of hours spent at home/work from each householder), leading to wider group scenarios. In fact, energy related behaviors are not only dependent on the number of inhabitants. Rather, factors such as oldness, number and type of electrical equipment, as well as presence of electrical heating systems (such as fan coils, heat pumps, air conditioners) and electrical boiler for domestic hot water production will heavily affect domestic energy consumption and pattern loads.

For each of the monitored users, an average 24-hour pattern load identifying typical household behavior regarding electricity consumption (smart meter) was created for every day, and a weekly mean value of the mean daily pattern load was deducted (Figure 7). Hence, pattern loads were distinguished from working days (from Monday to Friday in Figure 8) and weekends (Saturday and Sunday in Figure 9), since daily routine may vary with a large influence on electricity energy uses.

Results

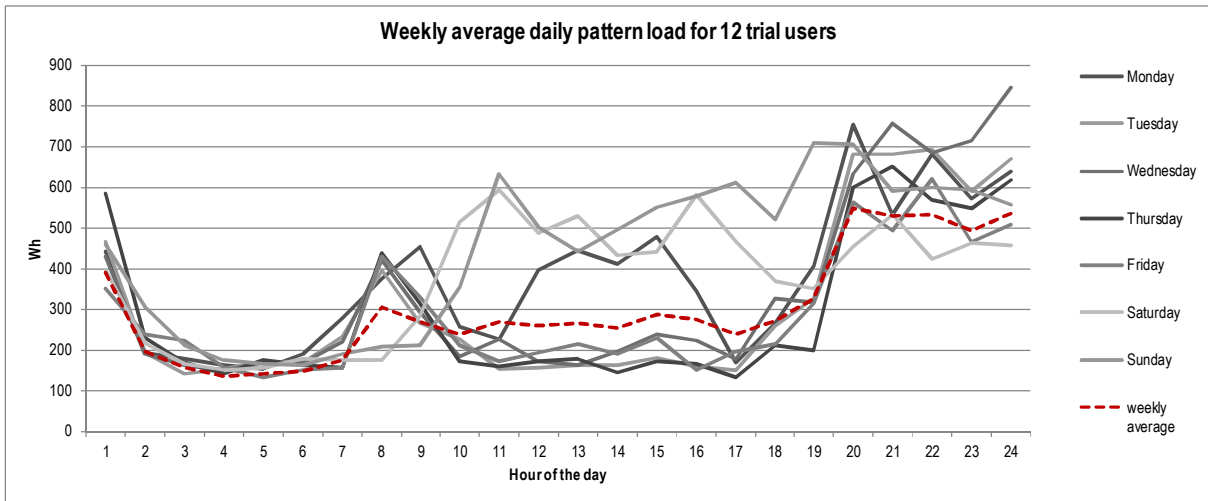


Figure 7. Weekly average daily pattern load for electricity consumption for 12 trial users (D'Oca et al, 2014)

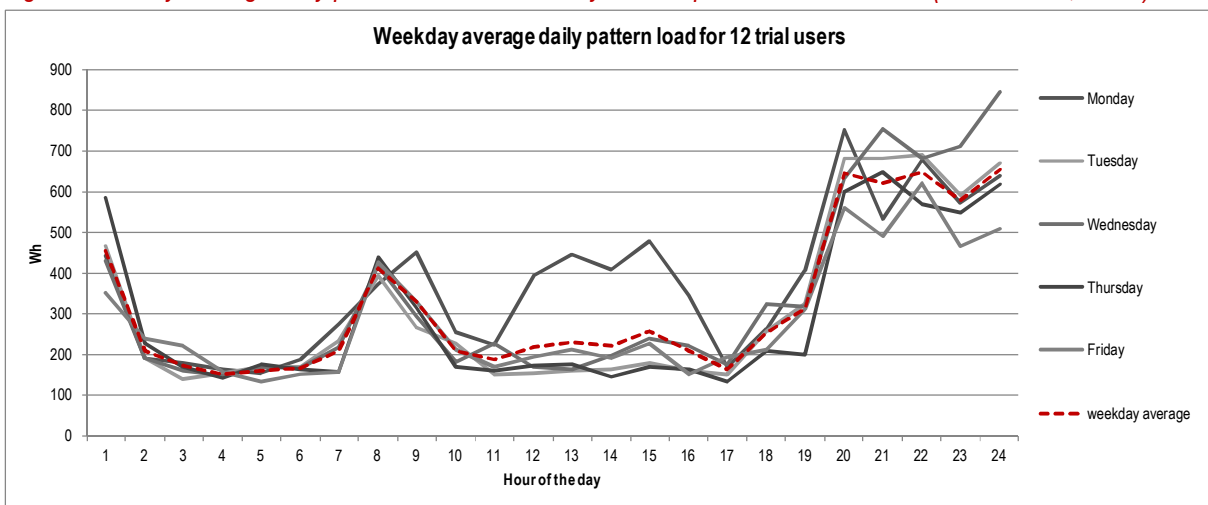


Figure 8. Weekday average daily pattern load for electricity consumption for 12 trial users (D'Oca et al, 2014)

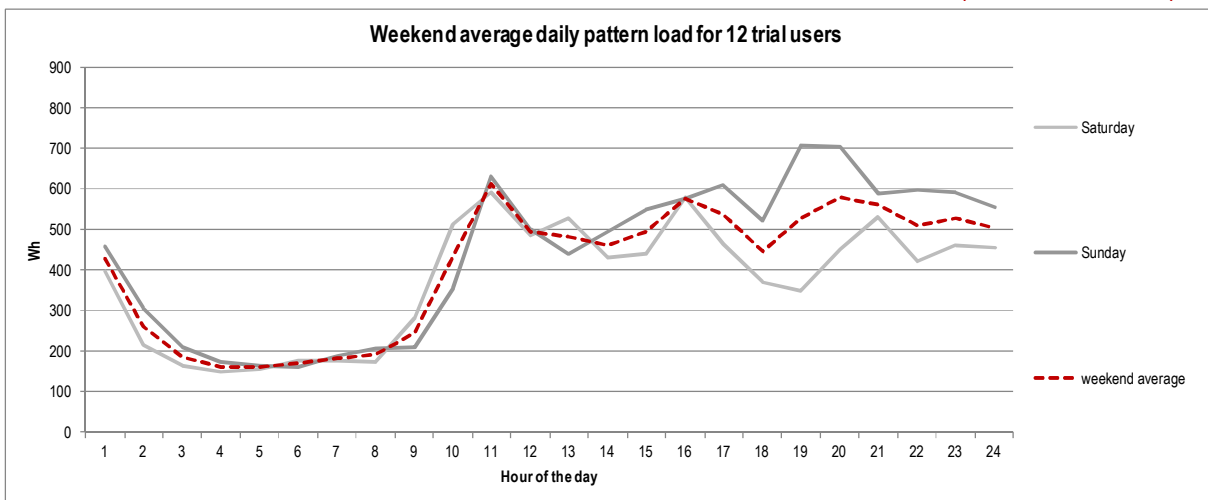


Figure 9. Weekend average daily pattern load for electricity consumption for 12 trial users (D'Oca et al, 2014)

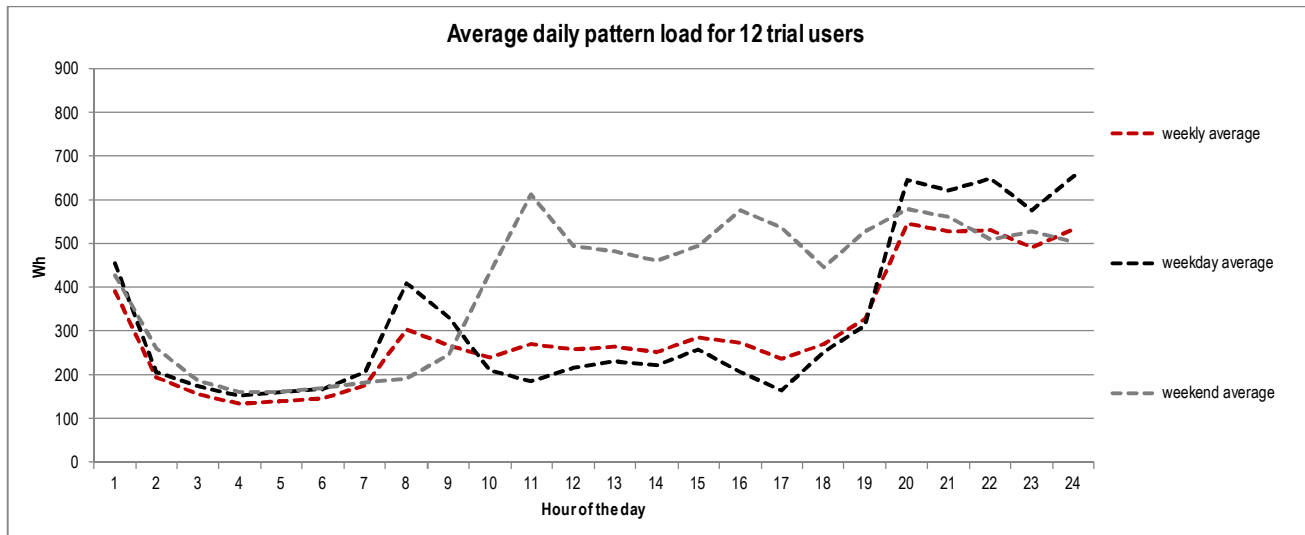


Figure 10 Average daily pattern load for electricity consumption for 12 trial users (D'Oca et al, 2014)

Finally, electricity load variation from weekday to the weekend was highlighted in figure 10. The black dotted line indicates the average consumption of the users during weekdays. The emerged pattern follows the typical daily routine of a working family during working days:

- peak in consumption between 7:00 and 10:00;
- standby consumption during the central part of the day;
- drastic rise in consumption from 17:00 to 20:00;
- very high but stable consumption between 20:00 and 24:00;
- fall of consumption in the night hours.

The grey dotted line indicates the typical consumption of the 12 users during weekends. The pattern follows the typical daily routine of a family during weekends:

- no peak in consumption due to wakening-time activities
- rise in consumption above 9:00 (late awakening) with a peak around 11:00 (generally associated with house cleaning and/or cooking activities)
- high but semi-stable consumption during the whole day until 24:00 with a deeper valley around 18:00 (nap time)
- fall down of consumption during the night hours.

Consumption pattern profiling

Based on the analysis of the average daily pattern loads for electricity consumption, for every family type, threshold values were settled based on typical consumption pattern ranging from “energy saver”, “on the average”, up to “energy intensive”. Not a singular value but a range of positive and negative values around the average were considered as significant for clustering the typical consumption pattern of the 12 monitored users. Specifically, a Buffer Acceptability Range (BAR) composed by three bands was created on a daily basis (Figure 11), regarding the whole week (Monday to Sunday). More accurate analysis was also performed related to week days and weekend, as well as for the smart washing machine and the appliances connected to the smart plugs.

- The first band corresponded to “average” consumption (yellow band)
- Two more bands were defined to identify a valid range of “energy intense” (red band) and “energy saver” (green band) typical consumption. For every hour of the day, higher and lower limits were settled around average values by adding and subtracting the standard deviation to the average values.

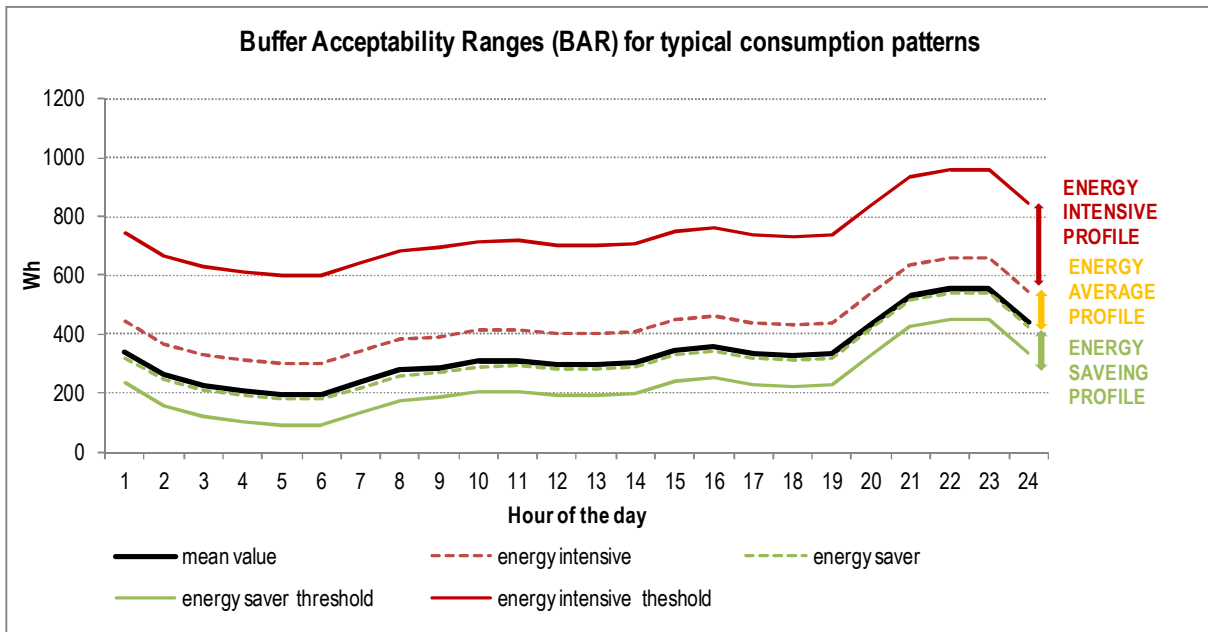


Figure 11. Buffer Acceptability Ranges (BAR) for typical consumption pattern ranging from “energy saver”, “on the average” up to “energy intensive” for 12 monitored trial users (D’Oca et al, 2014)

Evaluation of percentage of time in a BAR

The Buffer Acceptability Range for typical consumption pattern was used as self-reference value (horizontal benchmark) for the average electricity energy consumption of each specific family type. Daily average pattern loads of each of the users were overlapped to the BARs to provide users with a tailored information regarding their typical consumption pattern. The study, therefore, highlighted for how many hours of the day the electricity consumption of each user was bounded into as “energy saver,” “on the average” or “energy intensive” behavioral pattern (Figure 12).

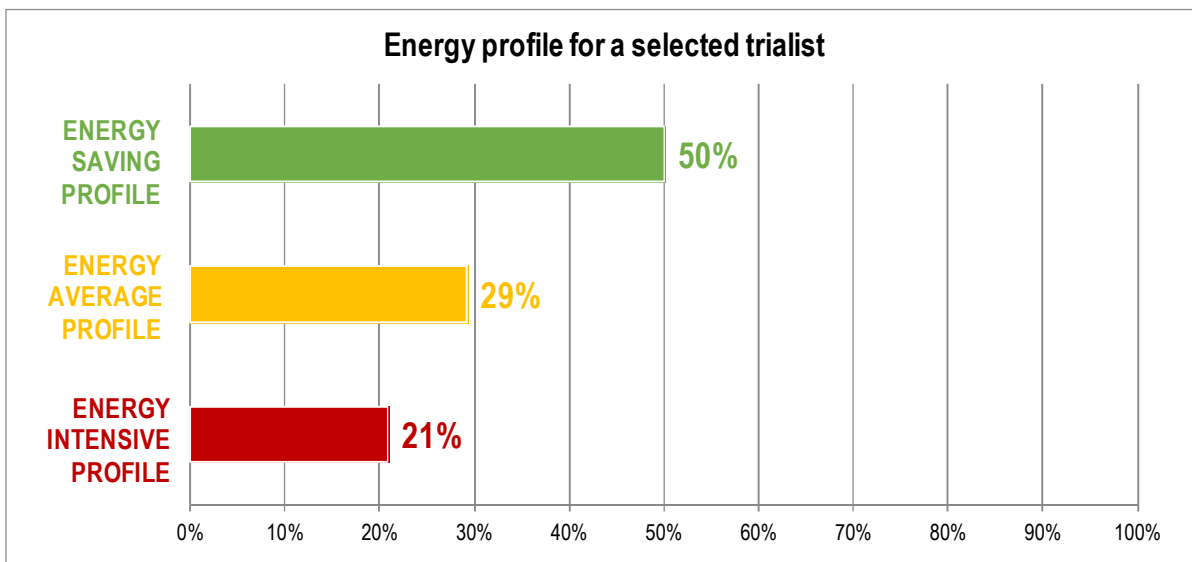


Figure 12. Target of energy profile for users based on electricity consumption during week days and weekend (D’Oca et al, 2014)

Qualitative KPIs. Evaluation of energy profiles

It is demonstrated that there is a social driver at work in the presentation of energy use in comparative fashion (Cuddy and Doherty 2010). If households learn they use more energy than similar family households, it is assumed they will be motivated to reduce consumption and possibly do more to reduce that usage. Targeted energy profiles of selected users

were plotted in the same graph, to perform a cross comparison between users having the same household composition (Figure 13). The aim of this qualitative indicator is to boost competition between households involved into a kind of «social-energy race», driving users towards more energy saving behavioral profiles.

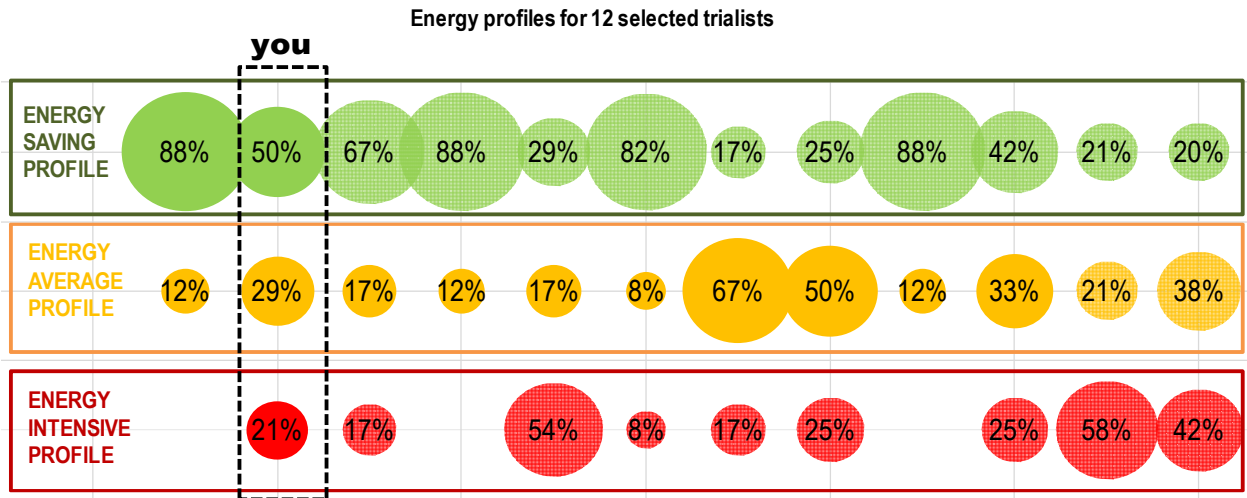


Figure 13. Qualitative KPIs. Comparison of energy consumption profiles for 12 users (D’Oca et al, 2014)

Qualitative KPIs Analysis of the global energy savings

Comparison between electricity consumption at the beginning of the monitoring period and an arbitrary date of ending period was performed. The energy consumption reduction was shown in the same graph, both concerning the percentage of energy reduction (Wh/week) and savings (€/week) (Figure 14).

In this way, users can compare their improvements (green arrows) or worsening (red arrows) in electricity weekly-based domestic consumption and compete to gain the highest improvements, in a sort of «social-energy race». The ideal goal of decreasing the electricity consumption in households should lead similar users to have electricity consumption similar or close to the lowest one.

An indication of the energy “intense”, “average” and “saving” energy profile ranges was hence plotted in the graph, to help users to understand the effect of changing habits and behaviors with respects to the energy consumption in their homes.

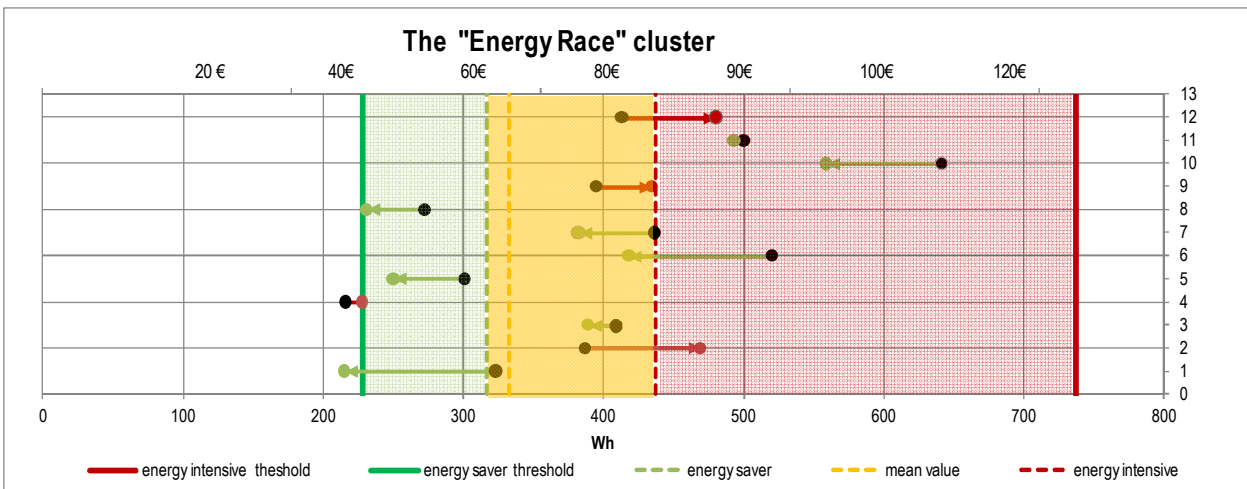


Figure 14. Qualitative KPIs. Energy race among a cluster of 12 users having same household composition (D’Oca et al, 2014)

Analysis of the newsletters' effectiveness

The main purpose of this study was to evaluate the energy saving potential at home by improving occupant's behavior in domestic life through energy-saving education and increasing user awareness in energy use. In this aim, several research questions have emerged, such as how frequently to share feedback information with users, in what form and unit to present the feedback, and where to display the feedback information (Patterson and Seaver 1976). With the aim of successfully motivating reductions in energy use from household consumers, besides the continuous feedback provided by the real time interfaces, a total number of 9 web-newsletters were sent via email to users in order to prompt them with a specific information (Table 1).

Table 1. Topics of the 9 newsletters (D'Oca et al, 2014)

Prompts on global energy consumption	Prompts on energy consumption with reference to family type	Prompts on stand-by energy consumption	Suggestion of actions to reduce stand-by energy consumption	Prompts on refrigerator energy consumption	Which is the most energy consuming appliance?	Prompts on smart washing machine energy consumption (Part I)	Prompts on smart washing machine energy consumption (Part II)	Visualization of changes in energy consumption load
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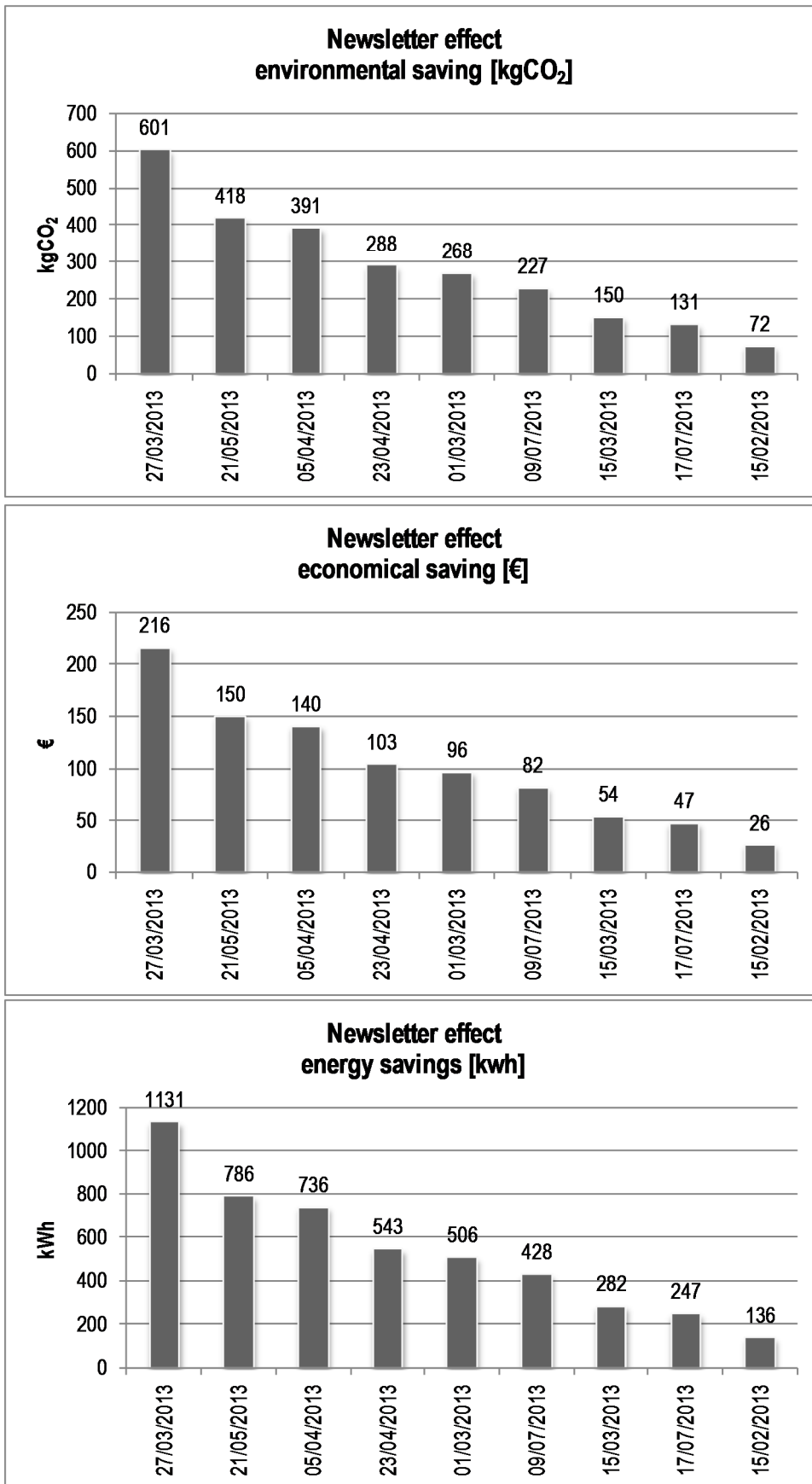


Figure 15. Process KPI. Global savings per Newsletter (D'Oca et al, 2014).

Outcomes: Occupant behavior energy savings

A good way to persuade consumers towards energy saving behaviors emerged by sharing how much energy they have used in one situation or period, and then using this information as a benchmark in the future with respect to households with comparable characteristics. This comparison is established as motivating the desire to better control energy consumption in the residential sector (OPOWER 2013).

In the developed newsletters, users were shown i.e. how to save electricity by managing standby power, suggesting those easy-to-take actions such as unplugging appliances, not in use, or setting refrigerator thermostat at the minimum level. Easy-to-understand graphs were provided to users, with the aim of enabling them to evaluate their improvements (or retrogression), on a weekly basis, during the monitoring period and compare them with those of similar families. The effectiveness of these newsletters in reducing energy consumptions was tested in a comparative fashion.

The efficiency of the first newsletter in reduction electricity consumption was calculated as the variation in energy use trends concerning the seasonal average. The effectiveness of the following newsletters in reducing electricity consumption was calculated as the change in energy consumption trends regarding the average energy consumption in the time step between the dispatches of two previous newsletters. In order to give evidence of the newsletters effects that enabled trial users in achieving the greatest energy savings on energy consumption variation, results were expressed regarding energy, economic and environmental savings. The most effective newsletter emerged as the one providing tailored information on stand-by consumption, also prompting them with suggestions on actions to perform to reduce the stand-by energy consumption in their homes. Conversely, the less effective newsletter arose like the one providing information related to energy consumption (Figure 14).

Results from the literature underlined that the energy saving potential of improving occupant behavior at home is on average around 15%. Results of the research undertaken by the author demonstrate that the system was effective in motivating users to change their behavior and generated savings of 18% on average (Figure 15).

This variation was calculated as the change in consumption from the first week of installation of the Energy@home kit to the last week of the testing phase.

If scaled up to the Italian national level, an average of 18% savings in the electricity consumption for all residential customers, would equate to up to 10.2 TWh of yearly savings, i.e. a saving in the national bill of about 2128 M€ - averaging 73 € in annual energy bill of every Italian electricity domestic customer. These savings correspond to the avoidance of 5.8 Million tons of CO₂ emissions and a value of the corresponding carbon offsets of 209,4 Million Euro, i.e. 9.2 €/customer, assuming carbon prices and current mix of Italian generation sources as of the year 2013 (AEEG, 2013).

One of the best “case history” users managed to lower their electricity energy consumption up to -57% during the testing phase of the Energy@home kit. A rapid fall in energy consumption was recorded in the very first weeks of usage of the smart monitoring system (Figure 18); however, even in the next weeks the user was able to exploit the system for further savings, which are significant in percentage. Significantly, this “fallback” effect (Wilhite & Ling 1995) emerged as “the phenomenon in which newness of a change causes people to react, but then the reaction diminishes, and the newness wears off” tends to diminish after the first week. After a rapid decrease, later on the testing period, energy consumption trend gradually and continuously lowered (Figure 16).

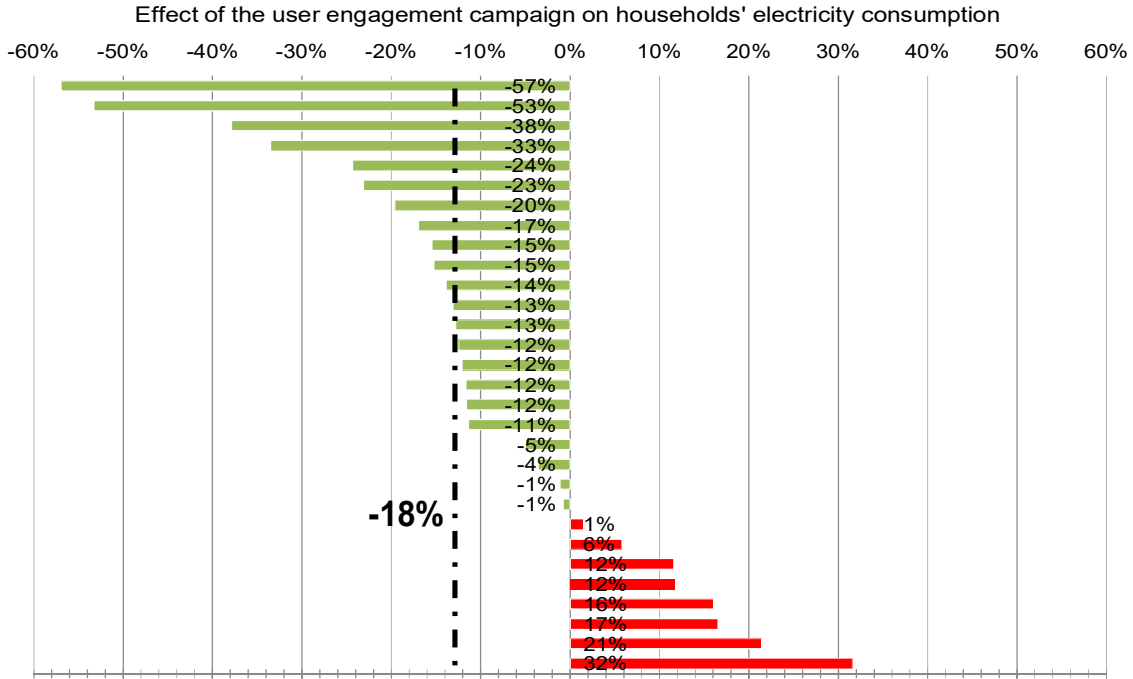


Figure 15. Variation in electricity consumption after the user engagement campaign conducted in 31 Italian dwellings having installed the Smart Monitoring in-home system (D'Oca et al, 2014)

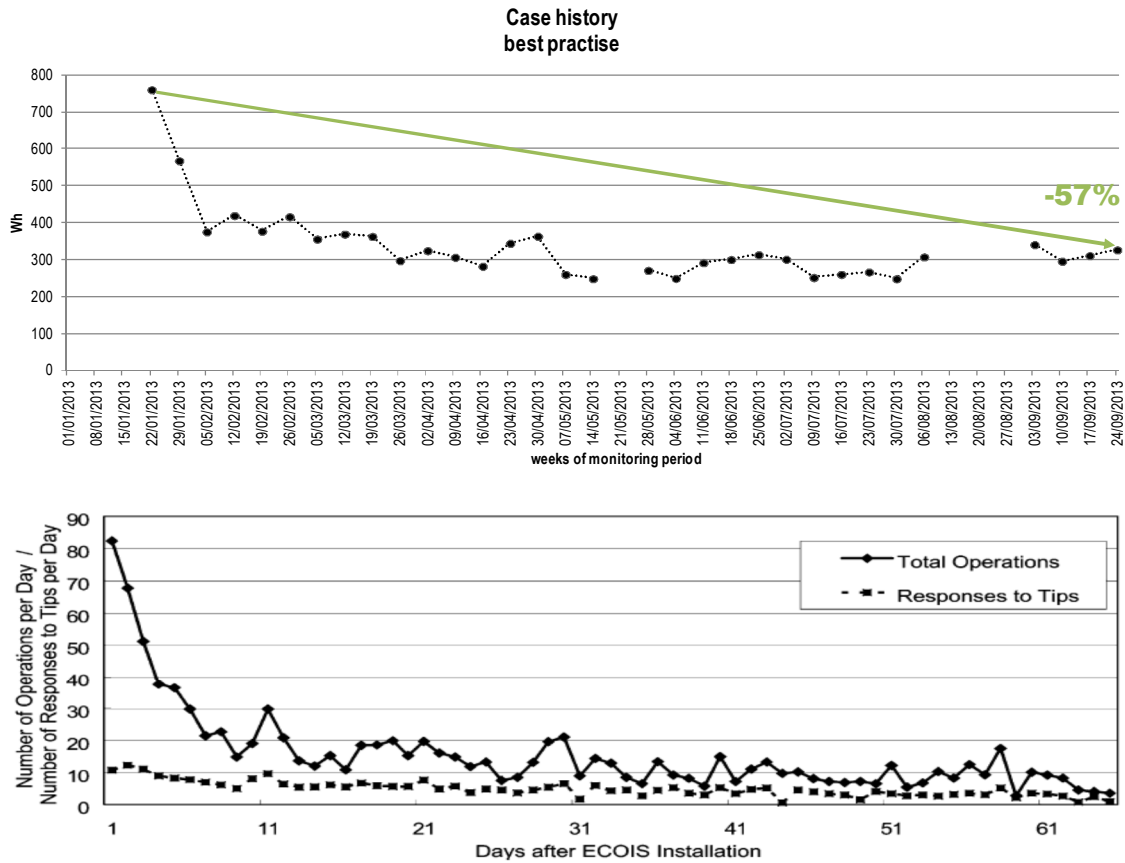


Figure 16. Fall back of energy consumption for best practice user, compared to the literature example (D'Oca et al, 2014 and Wilhite & Ling 1995)

The positive effect of providing users with visual information about their energy consumption is also underlined by user's feedback after the first week of monitoring. This tendency is supported by an active and involved participation of the user (and his households) in testing system functionalities and opportunities to reduce energy consumption. In some feedbacks sent through e-mails, the user stated:

- *"I consider the most useful information the one related to weekly consumption to control the trend in consumption. It would be interesting, if available, the overall consumption on the individual monitored plug to intervene if necessary in order to take measures to restrain consumption. I can say that from now on, after having realized the computer consumption, I am not going to leave it turned on when not in use any more".*
- *"I note with satisfaction that my refrigerator has the lowest consumption among experimenters, as it is a class A+ [equipment]."*
- *"The third graph shows that I mostly use the washing machine in the F1 hour-tariff. I alerted my wife about it, including helping her reading the graphics, in order to avoid as much as possible the usage of the washing machine in this range"*
- *"I showed the [washing machine load curve] graph to my wife, she says she is forced to use high temperature cycles for the 'white' otherwise cloths remain stained (e.g. tablecloths)"*
- *"As a virtuous [energy-saving] behavior, my wife says she tries to use the washing machine less and often taking advantage of every single full-load washing cycle and maybe this could be verified by your reports"*
- *"In order to reduce the stand-by power consumption, I intend to install a switch-on system for the TV plug and remove the led courtesy lights in the hallway that I have in my apartment, and then check the decline [in energy consumption]."*

Having a look to the energy consumption curve of this household, it is correct to state that he has positively reached his goal. As confirmation, *"buildings don't use energy: people do"*.

More detailed outcomes and discussion of the proposed study are presented in D'Oca et al [Paper 10].

Innovation: Engage occupants towards energy-savings behaviors and optimized controls in offices

Differently from the residential sector, engaging office users into more “forgiving” energy-saving and comfort-adaptive behavior is not a trivial task, since neither consequences nor benefits for changing behavior (i.e. increasing or reducing energy bills) have tangible effects on them directly (Healey 2013).

Rather than focusing on individual behaviors and influencing factors, effective solutions to engage occupants into more energy-savings profiles need to be nurtured with quantitative descriptions on the collective and social motivations within the complexity of different social groups in working environment, under different geographical context, culture and norms. In recent years, there has been improved attention in the application of behavioral theories borrowed from the social science and psychology to better understand behavioral change and to improve outcomes in these fields (Sovacool et al. 2015).

Behavioral change theories and models endeavor to enlighten the full picture around modifications and adaptation in individuals' behavior and behavioral patterns. These theories mention environmental, personal, and characteristics as the key aspects (or factor) influencing (also, driving) the human behavior. Similarly, researchers in the building science arena enlarged the perspective of the energy studies to the social science, recognizing the expanding power of provided recommendations for better interdisciplinary work with engineering and sciences (Sovacool 2014).

Paper 11

S. D'Oca, S.P. Corgnati et al.

Introduction to an occupant behavior motivation survey framework.

Proceedings of Clima2016 – May 2016

In order to engage successfully office users into energy efficient behaviors, research conducted in the context of this Ph.D. dissertation aims to discover a layer of social, contextual and group interaction constructs related to individual motivations. Motivation emerged as a key unlocking parameter for behavioral change, as largely discussed in the field of behavioral science theory (Gram-Hanssen 2014), (Onwezen et al. 2013). As described in the Theory of Planned Behavior (Ajzen 1991) motivations are driving behavior, and can be assumed as a proxy to describe actual behavior. Questionnaire studies conducted in the field of behavioral research (Harland et al. 2007), (Stern et al. 1986) also confirmed motivation can be assumed to be the immediate antecedent of behavior.

The research on building occupant behavior commonly focuses on direct observations such as sensing or other non-self-report data. In contrast, social science research deals with self-report data or latent variables such as motivations, beliefs, perceptions, emotions, and attitudes (Martinsson et al 2011). To the extent that perceived behavioral control communicated by the questionnaire respondents is veridical, it acts as a latent variable for actual control and can contribute to the prediction and estimate of the behavior in question. The goal of the study was to create an additional layer of standardized knowledge on energy-related behavior in office buildings, to enrich the state-of-the-art. An occupant behavior “motivational” survey framework is hence proposed as a standardized tool to base international data coverage collection of information on actual behavior in buildings and innovative results comparison.

The framework survey structure is primarily grounded on the DNAS ontology for energy-related occupant behavior in buildings (Hong, D'Oca, et al. 2015). This overlaps the four key components of the human-building interaction: i) the Drivers of behavior, ii) the Needs of the occupants, iii) the Actions carried out by the occupants, and iv) the building systems acted upon by the occupants. The questionnaire explores to what extent the occupant energy-related behavior in working spaces is driven by an individual motivational sphere influenced by i) comfort requirements, ii) habits, iii) intentions and iv) actual control of building systems (Figure 1)

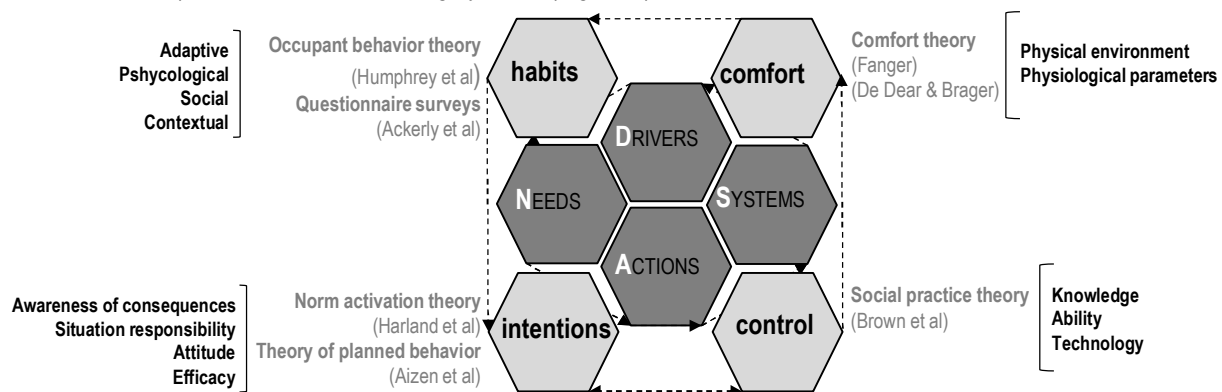


Figure 1. Structure of the OB Motivation Framework (D'Oca et al, 2015)

The occupant motivation survey is structured into 4 sections, corresponding to the framework structure (Table 1). For each section, the questionnaire defines i) the context of the question and allocates distinct ii) focus area categories, and provides background references, as follows:

Table 1. Structure of the OB Motivation Survey Framework (D'Oca et al, 2015)

Section	Context	Focus Area	References
Comfort	physical environment	thermal comfort	(Brager et al. 2004)
		visual comfort	
		IAQ	
	physiological parameters	gender	(Ole Fanger 1970)
	age		
Habits	adaptive	past behavior	(Ackerly & Brager 2012; Humphreys and Nicol 1998)
	psychological	response automaticity	
	social	social norms	
	contextual	workstyle routine	
		employment role	
		country of origin	
	environmental factors		
Intentions	awareness of consequences	perceived subjective norms	(Harland et al. 2007; Ajzen 1991)
	situation responsibility	perceived social norms	
	attitude	perceived willingness	
	efficacy	perceived effectiveness	
Control	ability	perceived control	(Brown & Duguid 2001)
		actual control	
		perceived access	
		perceived impediments	
		perceived achievements	

For a detailed description of the questionnaire surveys, readers might refer to D'Oca et al [Paper 12].

The future of occupant behavior studies remains a multidisciplinary and controversial field (Shove 2003; Chappells & Shove 2005), since comfort condition and energy use is recognized not merely related to physical parameters but also social and contextual factors. Accordingly, one of the main conclusions curtailing from this research, is that rather than focusing on individual behaviors – and influencing factors – research should focus on the rise and alteration of collective and social conventions shaped by geographical context, culture and norms, driving occupant motivations, as they are crucial in fastening behavioral patterns, with different consequences for building energy consumption and indoor environment comfort. Further advancements of the presented study is the operative rollout of an extensive survey questionnaire campaign in different geographical locations, among the international research community embracing the IEA EBC Annex 66 on “Definition and Simulation of Occupant Behavior in Buildings” (Yan & Hong 2014). The final aim of this study – in a broader perspective – is to provide a standardized tool to drive effective occupant behavior data collection, to enhance the state of the art on knowledge, methodologies and tools.

A comprehensive description of the survey questions and discussion of the proposed study are presented in D'Oca et al [Paper 11].

5. Discussion

5.1 Key takeaways and innovation fields

Extended studies conducted in the field of this Ph.D. dissertation indicate occupant behavior research is a leading contemporary topic aiming to narrow down the discrepancy between predicted and actual building energy consumption. Accordingly, the relationship between occupants, buildings, and the indoor environment requires being observed, understood and reproduced with appropriate approaches and techniques. In this contemporary picture, bringing the human factor in the loop of more technical and technological structural investments measures is foreseen as a cost-optimal action to improve comfort, enhance energy efficiency, reduce energy waste, and hence improving the overall energy performance of both existing and new buildings.

Together with the emerging behavioral studies of building physics, ICT, and the upward human behavior modeling expertise, a 'multidisciplinary knowledge' is hence proposed in this Ph.D. thesis as a promising field to draw critical expertise on the behavioral energy use phenomena in buildings. By adopting a multidisciplinary approach to the research, this dissertation had the purpose of filling the gaps of actual state-of-the-art, with major advancements in the field of sensing, analytical and modeling methods, simulation applications in building energy software, as well as user engagement techniques.

As a general observation, the conducted studies provided both qualitative and quantitative outcomes to be discoursed. All these pools of information, knowledge, insights and solutions appeared to provide an innovative understanding of occupant's adaptive actions. In the big picture, the future of occupant behavior research adopting such multidisciplinary approach is foreseen to be capable of supporting policy makers, designers, as well as the building construction industry in a wide array of current unresolved energy performance issues.

Key takeaways of the presented studies are discussed as in the followings.

Sensing Advancements: Methodological guidance for future user behavior monitoring through surveys

In discussing human behavior, researchers refer to stochastic responses to trigger events. These reactions are not random phenomena but occur following a determined tendency. The fundamental question is how to observe such tendency, to understand – and hence predict – the probability of a specific behavior to occur as a function of explanatory variables. Sensing building and human data is the new trend in building energy efficiency.

With the growing usage and technology development of connected devices in smart buildings and the increasing trend in self-monitoring, significant amounts of data are available in the construction sector. Data-driven techniques to gather real-time remote measurement of occupants' presence, movement, interaction with building technologies and usage of plug loads are rapidly expanding in both residential and commercial buildings.

On the one hand, physical sensors typically gather measurements of indoor and outdoor environmental data as well as smart metering (plug load, electricity) and building data (IEQ, energy loads). On the other hand, **including humans in the loop of sensing technology entails occupant's "passive" sensing** – i.e. occupancy sensors, monitoring interaction with control systems –, **as well subjective measurements techniques involving humans as "active" sensors** – i.e. asking directly occupant to self-report and to manage their interaction with building control system and building component.

Technology advancements are setting the stage of innovation in the field of human-building interaction observation. With respect to occupancy detection in building spaces, technologies can nowadays enable sensing and recognition of human presence, movement, and gestures leveraging i.e. on existing wireless sensor networks, connecting wearable sensors as well as virtual-reality know-hows, such as the Kinect technology.

Innovative sensing techniques of occupant behavior in buildings do not merely focus on monitoring individual behaviors – and influencing factors. Reporting plausible general behavior of a group of people might be more significant than exactly describe personal and isolated behaviors. Conversely, inventive research needs to focus on developing observation methods of collective and social conventions shaped by geographical context, culture and norms, driving occupant behavior, as they are crucial in fastening behavioral patterns, with different consequences for building energy consumption and indoor environment comfort.

To understand fully occupant behavior, based on facts rather than hypothesis, questionnaire survey emerged optimal tools for discovery of a layer of social, contextual and group interaction constructs related to driving forces and individual motivations. Direct subject questioning might overcome constraints of physical sensing technique to gather insights of multiple behavior interactions, i.e. the order of actions typically performed by the occupants to restore or bring about comfort conditions.

A trade-off between data accuracy and scalability is hence needed for achieving high impact results and bridging the credibility gap of energy efficiency in buildings.

By conducting a new, large-scale international transversal survey, many questions of our field can be answered. In this view, insights from social practice theories and techniques must be acquired to deploy robust and unbiased questionnaire surveys. Experimental subject observation methodologies, as well as techniques of data evaluation and data comparison criteria among countries, need to be established at the very beginning of the questionnaire design. This will ensure to provide innovative and universally acceptable information, knowledge, and insight on energy-related occupant behavior in buildings.

Analytical Advancements: Data mining techniques to discover patterns of energy-related OB in data set

Traditional methods of turning data into useful knowledge require data cleaning, analysis, and interpretation. However, such manual data analysis often becomes impractical, slow and expensive as data volume grows exponentially in the era of the *Internet of things* (IoT).

How to effectively translate building and human information into useful knowledge driving energy efficiency in buildings is still an open question. In a view of the complexity of human behavior, distinguishing singular diversity in big buildings becomes a challenging task. Parameter selection methods such as regression and correlation analysis are commonly utilized to identify the factors influencing occupant behavior in buildings and to cluster driver-response conditioning behavioral patterns. The strength of these statistical analysis techniques is their widespread familiarity among researchers and data analysts. Nonetheless, their outcomes are usually complex equations, which may not be easily understandable and interpreted, especially for non-expert users without advanced statistical knowledge (i.e. building operators and managers, building designers, energy modelers). Statistical analysis helps to identify repetitive behaviors, which may or may not be significant regarding schedules of operation incorporated into energy models. Moreover, “standard” behavior does not exist in the real world, and the concept of pattern encompasses much more than what is typically defined as expressions describing the most frequent behaviors in a building.

Given these facts, the Knowledge Discovery in Databases (KDD) have been demonstrated to presents an excellent opportunity for data analytics applications to discover new insights on the human-building interaction. The development of KDD methodologies and the application of data mining analytical techniques aimed to address the research community towards the choice of the best fit-for-purpose user type diversity profiles (stochastic profiles, agent/action-based model, standard schedules, archetypal user profiles) to be applied to different levels of modeling applications (building, block of building), aims of simulation (design, optimization, forecast, energy planning), building typologies (destination of use) as well as building-related factors (envelope, location, etc.).

The proposed data mining frameworks suggested an **improvement of the notion of behavioral patterns not only as statistical relevant driver-response conditioning clusters but as also incorporating the motivational dimension with typical window opening habits and occupancy in office spaces.**

In this context, cluster analysis gained information from key determinants for individual behavior by revealing a set of rules, which may allow assumptions on group behaviors that are more accurate and might overcome the lack of personalization of statistical methods. In a view of these facts, nevertheless the mined patterns of behavior were circumstantial to the given data set, the proposed frameworks were conceived generic enough to provide solutions to represent the diversity of typical office user profiles in real buildings. The further implementation of the discerned user profiles into building energy simulation tools is foreseen to provide an opportunity to establish an experience base for the assessment of real obtainable energy savings in buildings, equally in the design, retrofit and operation and maintenance contexts as well as for driving future energy policies.

Modeling Advancements: a standardized framework and syntax for modeling OB in BEMs

Advances in building energy modeling (BEM) engines allow a broad array of the most widespread simulation tools, such as EnergyPlus, IDA ICE, ESP-r, DeST, TRNSYS, DOE-2, to input tailored advanced models of occupant behavior in dynamic simulations. However, this is still a non-trivial task, even for expert modelers.

Several options are available, ranging from using pre-calculated deterministic inputs to the implementation of behavioral models as user function into the simulation engine. Diverse behavioral models capture building and occupant specific snapshot of reality, accordingly to dissimilar modeling methodologies scattered among published research, and no general agreement on the best fit-for-purpose modeling approach emerged. Moreover, there is no standardized coding language for implementing energy-related models of occupant behavior in BEMs.

The strengths and weaknesses of actual modeling and simulation approaches to occupant behavior have been analyzed and discussed. The critical analysis of existing models, the test of some illustrative example and a discussion of empirical and simulation outcomes of research lead to the conclusion that discrete-event Markov models could address a number of weaknesses observed other modeling approaches. However, the truthfulness and suitability of model selection emerged as a function of the specific use cases for occupant behavior modeling approaches. Some of the inappropriate use cases found in the literature have been highlighted and listed, in a way to drive modelers away from fallacies and misusages in future research. In these perspectives, future work recommendations are developed.

Advancements in the standardization of the quantitative descriptions and classification of occupant behavior on building performance have been initiated by this Ph.D. thesis. It is in this context that the DNAs framework was developed, together with the Simulation Research Group of Dr. Tianzhen Hong at the Lawrence Berkeley National Laboratory. Based on extensive literature reviews, the DNAs framework is a common information exchange ontology supporting stakeholders (architects, engineers, operators, owners, occupants) and policy makers, toward the standardization of the representation of energy-related occupant behavior. The final aim of the framework was to allow the incorporation of more accurate behavioral models into building simulation tools to provide comparable metrics and results. Applications of the DNAs framework include building energy modeling and simulation, building design, energy benchmarking and performance rating, development of codes and standards, and policy decisions. An XML schema called obXML was further developed as part of the presented Ph.D. study, **implementing the DNAs framework as a way to establish among the international community a common energy-related behavior language, which is both human and machine-readable.** On the long term, the obXML has the objective to promote comparison, sharing, and validation of occupant behavior models, while also facilitating their integration with different building simulation tools.

Further steps of research will embrace the application of a standardized ontology and data formatting for systematically including a large number of model forms – including but not limited to the ones discussed in this dissertation – to be shared with the research community as a whole.

Simulation Advancements: implementation of multiple stochastic models into building simulation tools

Typically, adaptive energy-related behaviors have been modeled in energy simulation tools using predefined rules and fixed schedules. When implemented in simulation tools, advanced behavioral models defined by means statistical analysis of real occupant- building operational data generate considerable variation on deterministic simulation. Whether this variation can be assumed as an improvement in accuracy of building performance prediction is still an open question. To this extent, two simulation studies, one for a residential building and one for an office building, implementing multiple advanced models of adaptive occupant behaviors - operating windows, blinds, lights, and adjusting thermostats - in a BEM simulation tool (IDA ICE), are proposed to support discussion around the topic.

Results of these studies gave confirmation to the hypothesis that occupants' behavior in buildings must be regarded as one of the key parameters of discrepancy between predicted and actual energy consumption in buildings. This is because some building occupants are very much aware of the drawbacks of their energy-related behaviors and habits, hence acting in ways to reduce their bill rather than to maintain a high level of comfort. In contrast, energy "careless" occupants might interact more liberally (or unconsciously) with the control systems to improve comfort conditions in their homes and offices.

Several research since the '70 engaged to the challenge of modifying occupant behavior in buildings. However, this strategy proposes solutions, which are independent from the building types and characteristics, but mainly leverage on the cognitive and physiological aspects of human behavior. A different approach begins in the energy simulation stage of the buildings, by testing design options for building envelope and system controls, which are able to guarantee the intended building energy performance, independently from the occupant's adaptive behaviors. In this view, the concept of **building robustness** does not imply occupants are not allowed to interact with building controls or only mechanical provisions of the indoor environmental quality levels are delivered. Rather, this concept supports the development of buildings, which are "occupant-proof" (O'Brien et al, 2014) meaning "less sensitive" to occupant behavior adaptive actions. Studies demonstrated that the effect of "careless" or "unaware" occupant behavior on energy consumption could be margined, when robust design solutions are employed (Karjalainen 2014; O'Brien 2013, Buso et al. 2015).

In this view, outcomes of this study are aiming to support building designers, architects and engineers, to design building that are – on the one hand – less sensitive to occupant adaptive behaviors when simulated behavioral controls are indicating uncertainty in energy consumption variation, and to profit – on the other hand – from the energy reduction potential of behavioral adaptation mechanisms.

Moreover, despite the circumstantiality of results, findings of this research generalize that occupants' interactions within building envelope and control systems are strictly interrelated to the pursuit of personal comfort, the perceived indoor environmental quality and therefore global energy performance of the buildings. For the practical point of view, the main aim of emphasizing this variability was to stress the big issue of the occupants' role in actively modifying buildings' performances in real life operation. The availability of occupants' behavioral models to simulate variation parameters associated with specific building features or climate can give a hint of the actual energy performances fluctuation of the building object of analysis. In a broader perspective, this might help in bridging the accuracy gap between predicted and actual building energy performance (consumption and comfort).

User engagement Advancements: behaviorally driven energy savings in buildings

On September 2015, the White House Office of the Press Secretary released an executive order for “using behavioral science insights to serve better the American People”. This evidence demonstrates that behavioral insights might be used to improve outcomes of even deeply technical fields and to delivered better results at lower costs. This might help to accelerate the transition to a low carbon economy – not merely in the sphere of energy efficiency measures in building, as the case tackled in this Ph.D. dissertation. The executive nature of the order then reflects the urgency to drive people towards more conscious decisions.

For anyone interested in human behavior and energy savings, this order is a milestone testifying the growing importance of behavioral science to improve bottom-up approaches to enhance technical programs effectiveness.

The concept of displaying energy consumption to building occupants with a view to promoting energy saving behaviors is not new. Since the 1970s, a number of strategies have been encouraged and tested. These include historical, and real-time energy breakdown feedback, as well as comparative goal settings, to provide motivational feedback of positive or negative consequences of behaviors. A good way to persuade consumers towards energy saving behaviors emerged by communicating how much energy users have used in one situation or period, and then using this information as a benchmark in the future, or on households having comparable characteristics (Van Houwelingen and Van Raaij, 1989). Results from the literature reviewed underlined that the energy saving potential for improving occupant behavior at home is on average around 15%.

In accordance, outcomes of the research undertaken by this Ph.D. study demonstrated that smart monitoring system employing user engagement techniques can be effective in motivating domestic users to change their behavior and generated savings of 18% on average.

However, differently from the residential sector, engaging office users into more “forgiving” energy-saving and comfort-adaptive behavior is not a trivial task, since benefits (i.e. economical) for shifting towards energy saving behavior have little tangible effects on them personally. Also, consequences can be negatively experienced regarding loss of comfort and reduction of productivity and satisfaction in the working environment. Accordingly, rather than focusing on individual behaviors and influencing factors, effective solutions to engage occupants into more energy-savings profiles need to be nurtured with quantitative descriptions on the collective motivations within the complexity of different social groups in collective environment, under different geographical context, culture, and norms.

6. Conclusions

6.1 Highlight benefits of the multidisciplinary approach to the research arena

How will the multidisciplinary approach triangulated from the building-data-human systems to study energy-related behavior in buildings will enhance the state of the art to provide benefit to the research arena?

Diverse applications and case studies have been illustrated and discussed throughout this Ph.D. dissertation to sew up a 'fil rouge' combining independent investigations into a meaningful map of valuable discoveries, measurable insights and effective solutions aiming to bridge the gap between actual and expected energy efficiency in the building sector. In this context, this Ph.D. dissertation targets to set the stage for occupant behavior in building as the innovation paradigm for energy efficiency of the built environment towards 2020 nZEB and 2050 post carbon goals.

Specifically, it leverages the potential of significant energy conservation opportunities, by integrating humans-in-the-loop in building design, sensing, and control, as well as using behavior awareness as an energy efficiency measure in buildings. Outcomes of literature reviews, data analysis, and energy simulation scenarios including quantification of occupant behavior impacts, such as energy saving potential and hidden energy and comfort drawbacks, will support building energy designers, modelers, operator and manager to develop specific energy efficiency measures.

Moreover, proposed solutions and insights aim to evaluate technology adoption levels, by taking into account the bearing power of building occupants. In addition, the knowledge discovered seeks to support energy and urban planners in the creation of more informed energy policies, programs, codes and standards (i.e. technology driven incentives and retrofit measures) and the development of robust energy planning tools targeting energy efficiency in building experience (Figure 1).

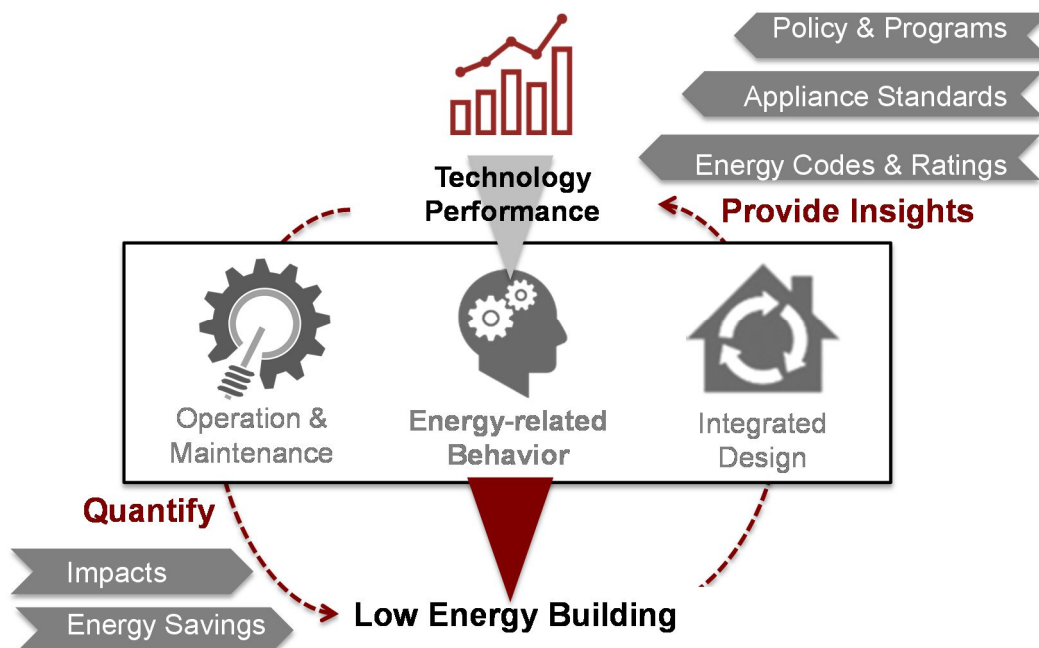


Figure 1. Schematic Overview of targeted outcomes research approach (Hong, D'Oca et al, 2015)

6.2 Picture main challenges of research

State-of-the-art research typically examines the concerns about the “occupant behavior” into independent parts through the disciplinary lens of building science, behavioral science, data science. Nonetheless, given the complex nature of human behavior and building physics studies, this approach leaves some unresolved questions, meaning **that an innovative research methodology is required. This approach must have the capability to enable a multi-dimensional yet specific understanding of each field of the investigation.**

There is a growing interest in the enhancement of an integrative research approach investigating the human and energy interaction (Stern 2014). Some interesting insights into the understanding of energy-related behavior have been recently provided from data and social science, psychology, and behavioral theories (Sovacool et al. 2015).

In this context, and without the presumption of holding holistic knowledge in the different fields, this Ph.D. thesis discussed how pro-actively to address the many challenges that such multidisciplinary research ground faces. The research presented in this Ph.D. dissertation had the ambition to push the boundaries of fundamental knowledge and isolated research approaches. The primary goal of the thesis was to clarify the composite interlocking of the various dynamics connecting the human factor to energy efficiency in buildings. By providing a holistic and innovative acceptance of research, this thesis tried to move beyond traditional disciplinary approaches.

Accordingly, not one-size fits all theory was presented in this thesis, but an interdisciplinary, integrative, pluralistic approach was conducted through the three years research, to deliver contextual responses to individual issues. With any doubt, the theoretical understandings borrowed from the interconnected fields of study were not intrinsically innovative or new. Nevertheless, the main problems and constraints related to the human factor might have been already addressed in **separate areas, which are not naturally exchanging information with the architectural engineering sector.**

At present, the International Energy Agency is seeking to promote such an approach by funding the Annex 66 “Modeling and Simulating Occupant Behavior in Building”. IEA Annex 66 is moving significant steps to develop a **research-integrative research arena, which is international and multidisciplinary.**

This will help to gather scientific insights around the role of occupant behavior in the building sector.

6.3 Potential for future research

The mission of this Ph.D. thesis was developed under the research framework of Annex 66 that is currently in progress, and through a consultative process among the stakeholders of such international scientific community. **This has not been a simple task. However, it has been an enriching working and life experience.**

Challenges and future steps of the presented dissertation will aim to translate the research outcomes into effective deployments having measurable impacts on individual, group and collective behaviors to improve building energy efficiency in residential and commercial buildings. Scalability of the solution is foreseen from the zone to the block of building level.

Doctorate research activities will forge ahead with a Post-Doctorate Fellowship offered at the Simulation Research Group of the Energy Technology Division of the Lawrence Berkeley National Laboratory, Berkeley.

The Post-Doctorate research will focus on demonstrating the effectiveness of real-time sensing technology in developing hierarchical occupancy-responsive predictive control strategies at different building levels. Research activities will specifically apply to analyze real-time sensors data to predict occupants' movement and energy behaviors such as interaction with building services systems, to improve their comfort and reduce energy use, as well as to provide two-way communication between the MPC data system, the engaged building occupants, and the sensed building systems. Further research aims to provide answers to some open question remained unresolved by this Ph.D. dissertation, such as:

- How to gain insights from data science and IoT to foster energy efficient occupant behavior in buildings?
- Which behavior has a significant influence in which building type?
- How much occupant behavior varies among cultures and climates?
- How to represent the social and contextual interferences of group behavior?
- How to overcome constraints to multiple behavior simulations, such as the order of actions?

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

6.4 Final remarks

Humans are responsible and capable of tackling the climate change our world is confronting with, by adopting energy consumption paradigm shifts. Enormous amounts of behavioral opportunities are available to act towards the energy mitigation challenge. We can picture two parallel universes related to energy-related behavior mitigation strategies. On the “Action” side, business strategies, awareness campaigns, and technology investments can raise energy-conscious behaviors at the building level (residential, office, commercial), as well as cities can act on climate change mitigations at the urban level. On the “Norm and Standards” side, effort must be made to transform these sets of actions into regulatory norms for a global behavioral energy mitigation agreement.

The transition needs to be fostered in a broad spectrum of arenas to reduce the carbon footprint of energy-related human activities in buildings: both in the living (how people behave in their homes or during vacation, i.e. in hotels) and working environment.

However, despite the burgeoning interest and sensitivity to environmental concerns of actual trends of energy consumption paradigm worldwide, average people ask for comfort in their homes, no matter what the cost nor the consequences of daily routine or habits. Similarly in office building– from CEOs to front-line workers – all employees behave in an unconscious energy-intensive manner, i.e. leaving their PCs and lights on when not in the office, opening a window when arriving the office to provide fresh air, no matter the HVAC system is still running. It becomes tremendously difficult to rewire the human brain to unlearn such energy-wasting patterns of behaviors and to initialize a path towards more “motivated” energy-conserving habits and routines.

Individual building users can act just up to a certain level. This changeover must be scaled up to wider urban level, to leverage the positive impacts of behavioral mitigation strategies: i.e. how universities run their campuses, or how cities manage their energy loads. The energy market, the building construction sector, and the policy regulatory arena need hence to work jointly, to allow people to make this switch run.

Designed energy efficiency measures over decades have been documented as being deviated from reality, relying on assumptions of rationality and determinisms when referring to human behavior. This has led to suboptimal policies in the past. Differently, this trend needs to be promoted with a fresh look into architectural engineering, data science, and behavioral insights to achieve a shift in the energy consumption paradigm towards a low carbon future satisfactorily.

Accordingly, with a view to meet the 2020 and 2050 decarbonization targets, this Ph.D. dissertation foresees the need to foster dedicated behavioral science policies in the building sector (i.e. Energy Performance Occupant Directive EPOD), besides more traditional Energy Performance Building Directive – such as the UE EPBD. Solutions illuminated by this Ph.D. thesis supported the concept that energy efficiency in buildings is not merely a technology issue. Conversely, policies and programs leveraging of building science knowledge, data science insights and applying behavioral science resolutions to building energy performance might yield improvements in program cost-effectiveness, as well as the development of more robust energy conservation strategies. Rigorous testing and evaluation of impacts and outcomes of such strategies must be employed to test the effectiveness of results.

6.5 Main achievements

This Ph.D. thesis illuminated how a multidimensional approach triangulated from the building-data-human systems to study energy-related behavior in buildings can enhance the state of the art to provide advancements in energy efficiency - to the same extent of technology innovations in the construction sector. This has been done by setting the stage for occupant behavior in building as a central part of the innovation paradigm for energy efficiency of the built environment. Main innovations can be summarized as follows, in terms of methodology, procedures and numerical evidences of the proposed research.

Methodology

Typically, research on the human factor on energy uses focused on technical or purely social research approaches. Progressing past that, this research integrates occupant behavior in a multidisciplinary methodology that combines insights from the technical, analytical and social dimension. This is achieved by combining building physics (occupant behavior simulation in building energy models) and data mining analytics (occupant modeling and profiling) with behavioral theories (occupant engagement) to provide multidisciplinary innovative procedures and numerical evidences on human-centered energy efficiency in buildings.

Procedures

The procedure of knowledge discovery in human-building database by employing data mining techniques is suggested as an improvement of the notion of behavioral patterns not only as merely statistical relevant clusters but also incorporating the driver-response conditioning dimension with typical behavioral habits.

Behavioral model validity and transferability is established by means the creation of a common standardized framework among the international community, unfolding the cognitive dimension of occupant-human interaction through Drivers, Needs, Actions and Systems (DNAs).

Grounded on the DNAs framework, a human-machine readable syntax (XML language) for representing a comprehensive library (obXML) of energy-related occupant behavior in buildings is developed. When implemented into current building simulation tools, validated behavioral models are intended to bridge the credibility gap of building energy performance

Numerical evidences

Outcomes of energy simulation scenarios demonstrated the variability in energy consumption simulation, by switching from a traditional deterministic approach to a probabilistic consideration of occupant behavior in residential buildings (up to 60%). In addition, it included quantification of occupant behavior impacts (22% on average), such as the potential for energy savings and hidden energy and comfort drawbacks.

Moreover, leveraging on improved communication on energy usage and IEQ between the building-data-human systems, behavioral science insights are applied to engaging energy-aware behaviors in residential buildings to save on average 18% on the annual domestic electricity bill.

Innovative methodological research approach, procedures and numerical evidences aim to support building energy designers, modelers, operator and managers to develop specific energy efficiency measures, and to evaluate technology adoption levels, by taking into account the importance of the human factor on building energy use.

Recognition and validation of the proposed multidisciplinary research approach



The multidisciplinary research approach proposed in this Ph.D. dissertation has been adopted by the H2020 project **MOBISTYLE** “*MOTivating end-users Behavioral change by combined ICT based tools and modular Information services on energy use, indoor environment, health and lifestyle*”, to improve the understanding of occupant behavior and cultivate energy efficient behavior in buildings (2016-2019).

The overall aim of MOBISTYLE is to motivate behavioral change by raising consumer awareness and by providing attractive personalized combined pro-active knowledge services on energy use, indoor environment, health and lifestyle, by ICT-based solutions. Measurable benefits raises behavioral change by the awareness of feedback loops. This awareness will support and motivate end-users to well informed proactive behavior towards energy use and health, thus empowering consumers and providing confidence of making the right choices. The combination of awareness on energy, health and lifestyle will offer consumers more and lasting incentives than only information on energy use.

This **project embraces** the methodology proposed in this Ph.D. dissertation to integrate occupants' behavioral impacts on building energy use into **data collection, analytics and modeling, energy simulations and solutions** (insights and feedback), as follows:

- I. Investigate the operation of energy systems through behavior-related building data collection. A common data collection and analysis framework is based on:
 - building energy and IEQ (building sensors)
 - occupant comfort and health (wearable sensors)
 - monitoring of human presence and practices (window opening, control of heating and cooling, natural ventilation behavior, shading, etc.)
- II. Understand the human behavior (comfort, health) through user data analytics (using data mining techniques), stochastic modeling, and energy simulations. The energy and environmental monitoring and data analysis have following main objectives:
 - Transform gathered energy and IEQ data into useful knowledge to raise awareness (energy, IEQ, comfort, health) for the building users
 - Develop, validate and deploy methodological approaches able to evaluate and predict the operative energy and environmental performance (IEQ) of a building based on monitoring and awareness campaign (building and user data)
 - Develop benchmarks for deepening diagnostic and investigation on punctual criticisms
- III. Propose solutions to overcome energy and environmental inefficiency due to poor operation or lack of information. Final aim is to improve the building performance (energy, thermal comfort, IAQ) by integrating behavioral solutions (awareness campaign). A common approach is established to assess evaluations and to test the effectiveness in reducing electricity consumption, enhancing IEQ and therefore augmenting user comfort and health by combining ICT information with persuasive tailored feedback in different case study buildings.

The project shared methodology will be tested and validated among **five different pilot case studies** varying because of location, climatic areas, buildings typology and scale, energy use intensity and intended use (residential, educational, hotel, health care).

Over the duration of 36 months, this project targets to provide energy efficiency benefits to the building sector with a new range of innovative technical services, which bring building monitoring, control equipment, smart meters and pioneering human-in-the loop interactive and tailored information together.

This range of human-building products is foreseen as a strong support to the implementation of the EPBD/EED in the face of achieving 2020 and 2050 energy conservation goals in the building sector.

The adoption of the proposed multidisciplinary approach by a H2020 European Project provides an esteemed and trusted recognition to the methodological structure of this Ph.D. dissertation. Moreover, it provides accomplishment to the primary goal of this Ph.D. study, highlighting the human factor in energy use as a fundamental aspect influencing the energy performance of buildings and maximizing energy efficiency – to the same extent as technological innovation.

Going further, the development of the project will illuminate some practical ways to transform theories, analytical methods and simulations developed in the context of this PhD dissertation into real pilot study applications. Moreover, in a broader perspective, it will deliver ground to validate and test the effectiveness of enhanced human-building interaction as the innovative energy efficient paradigm in the building sector.

Research activity conducted in cooperation with other Universities, Research Centers and national/international Industries

The three-year Ph.D. research directed the development of expertise in fundamental research such in University Institutions (Polytechnic of Turin) and research laboratories (LBNL, Berkeley) as well as applied research: IEEM Indoor Environment and Energy Management - Telecom Italia Competence Centre (Polytechnic of Turin). Almost half of the Ph.D. program (15 months) has been spent by the Simulation Research Team of the Building Technology and Urban System Division lead by Dr. Hong, staff scientist at Lawrence Berkeley National Laboratory, and operating agent Annex 66, "Definition and Simulation of Occupant Behavior in Buildings.

Activities developed at LBNL included the application of data mining and statistical analysis techniques on building occupant energy-related behavioral big data sets, presenting results to seminars among the Environmental Energy Technology Division, contributing to weekly update meeting with the Simulation Research Group, and disseminating results of the research. The role in the research team mainly relied on written communication of the research, including:

- writing proposals leveraging the human factor on building energy use - for the US Department of Energy and the California Energy Commission;
- 5 articles published and 3 to submitted in international peer reviewed journals;
- 3 conference articles presented in international conferences

The remaining Ph.D. program focused on developing fundamental research, in collaboration with the TEBE Group of Department of Energy (Polytechnic of Turin), under the supervision of Prof. Stefano Corgnati. Research activities mainly focused on modeling and simulation of energy-related occupant behavior in buildings, organizing international workshops on occupant behavior studies with academic partnerships, participating in international conferences, presenting peer-reviewed articles, as well as providing lectures to master classes of building physics and sustainable building construction.

Expertise in applied research has been established thanks to the collaboration with the IEEM Indoor Environment and Energy Management - Telecom Italia Competence Centre (Polytechnic of Turin).

Here, research activities concentrated on smart metering, plug loads, energy visualization programs and feedback in buildings. This work of Energy Department of Politecnico of Torino – named Energy@home - was supported by a research contract of Telecom Italia (Progetto Pangea, 2013). Author thank Telecom Italia, Enel Distribuzione, Indesit Company and the Energy@home Association for making data available and for sharing analysis and results published in the context of this dissertation. Research activities included data analysis and interpretation, and development of survey questionnaires for strategic decision-making, as well as follow-up and results presentation of technology-transfer projects to partners.

Additional research activities undertaken (national and international research projects and/or contracts)

From 2012 to 2013, I have been involved into the International Energy Agency - ECBCS Annex 53 "Total Energy Use in Buildings" Project.

From 2013 to 2016, I actively participate in the annual meetings of the IEA EBC project "Annex 66 "Definition and Simulation of Occupant Behavior in Buildings".

These projects focus on the study of energy-related behavior in buildings and encompass multidisciplinary fields such as building physics, energy models as well as the psychology of consumer behavior. Both projects involved more than 24 countries and 57 organizations including universities, research institutes, software companies, design consultant companies, operation managers, and system control companies. In this context, expertise to devise and coordinate a collective work

Cooperation and/or support to teaching activities at this University

Doctorate activities included support to lectures to master classes of building physics, civil engineers and design units of sustainable building construction. Lectures covered key topic related to the impact of occupant behavior on building design, energy modeling and retrofit phases, human-building interaction and control system, methodologies for measuring occupant behavior and IEQ in indoor environments, theoretical introduction to the thermal comfort theories in building.

Most relevant courses and seminars attended (internal, external to the University, and so forward – just mention the type and number of courses/seminars)

	Titolo del corso	Codice corso	Docente	CFU	Attivazione
Corsi III ITAC 12 CFU	ASPETTI TECNOLOGICI E ARCHITETTONICI DELLA COSTRUZIONE SOSTENIBILE I	01MJFKN	V. Serra	6	Maggio 2013
	COMPETITIVE RESEARCH GRANTS: FROM THE IDEA TO THE PROPOSAL	01PJNKG	A. Anfossi	2	Gennaio 2015
	ETICA INFORMATICA	01PJMKG	R. Patrignani	4	Marzo 2015
Corsi di III livello 10 CFU	DATA MINING: CONCETTI E ALGORITMI (Dottorato di ricerca in Ingegneria Informatica Sistemi)	01LBZIU	E. Baralis	4	Settembre 2013
	BEHAVIORAL THEORIES (Dottorato di ricerca Smart Building and Smart Cities)	01QTVRS	C. Pronello	3	Febbraio 2015
	ANALISI STATISTICA DEI DATI (Dottorato di ricerca in Ambiente E Territorio – Torino)	02KZZKL	T. Bellone	3	Luglio 2013
Didattica di Eccellenza 8 CFU	URBAN STUDIES FOR SMART CITIES	01PSWKL	P. Lombardi	3	Settembre 2013
	SMART CITY METRICS FOR THE EVALUATION OF THE URBAN MORPHOLOGY	01QPPRS	P. Lombardi	3	Gennaio 2015
	DISTRIBUTIONAL DATA ANALYSIS (Dipartimento Scienze Matematiche DISMA)	* in attesa	M. Gasparini	2	Ottobre 2015
Totale				30	

Training periods outside Politecnico (type of training, place and duration)

Denominazione Attività esterna	Ore	Crediti	Data attività
International Summer School on Sustainable University Campuses- Polito	30	6	13/9/15
Predictive Modeling Network for Sustainable Human-Building Ecosystems A Research Coordination Network, II Workshop, Berkeley, CA (US)	18	3	1/4/15
IEA EBC Annex 66“Definition and Simulation of Occupant Behavior in Buildings” workshop - LBNL, Berkeley, CA (US)	10	2	11/6/14
EA Annex 66 - Definition and Simulation of Occupant Behavior in Building 1st Expert Meeting, Hong Kong	20	4	11/3/14
Predictive Modeling Network for Sustainable Human-Building Ecosystems A Research Coordination Network, Workshop I, Charlotte, North Carolina (US)	20	4	26/5/14
Scuola Estiva di Fisica Tecnica di Benevento	32	6	7/7/13
Totale		25	

Corsi convalidati	30
Attività esterne convalidate	25
Totale Crediti Acquisiti	55

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