AN INVESTIGATION INTO BUILDING OCCUPANT BEHAVIOR OF DIFFERENT HOUSEHOLD TYPOLOGIES IN ARCHITECTURE

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ABSTRACT

AN INVESTIGATION INTO BUILDING OCCUPANT BEHAVIOR OF DIFFERENT HOUSEHOLD TYPOLOGIES IN ARCHITECTURE

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Humans who directly interact with the built environment are a significant parameter of the architectural design process. The uncertainty in occupant behavior is a variable parameter of sustainability in architecture. Human building interaction affects energy consumption and creates an unpredicted result for the building's calculated energy use. The interaction between the occupant and the building is significant for establishing new areas of architectural inquiry. The study aims to observe the influence of occupancy behavior with various type schedules on building performance. Occupancy, equipment, and lighting schedules are modeled and simulated to investigate the energy consumption of residential buildings. The thesis is influenced by the changes in daily life due to the Covid-19 pandemic and lockdowns. Different household cases are modeled with post-pandemic conditions and analyzed to the conception of the role of the occupant in actual energy consumption.

Keywords: Occupant Behavior, Human-Building Interaction, Occupancy Schedules, Building Performance Simulation, Household Typologies

ÖZ

MİMARLIKTA FARKLI HANE TİPOLOJİLERİNDEKİ BİNA KULLANICI DAVRANIŞLARININ İNCELENMESİ

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Yapılı çevre ile doğrudan etkileşime giren insanlar, mimari tasarım sürecinin önemli bir parametresidir. Kullanıcı davranışındaki belirsizlik, mimaride sürdürülebilirliğin değişken bir etkenidir. İnsan bina etkileşimi enerji tüketimini etkiler ve binanın hesaplanan enerji tüketimi için öngörülemeyen bir sonuç yaratır. Kullanıcı ve bina arasındaki etkileşim, yeni mimari araştırma alanları oluşturmak için oldukça önemlidir. Çalışmanın amacı, çeşitli profildeki kullanıcı davranışlarının bina performansı üzerindeki etkisini gözlemlemektir. Konut binalarınındaki enerji tüketimini incelemek için kullanıcı, ev aletleri ve aydınlatma çizelgeleri oluşturulmuş ve simülasyonlar yapılmıştır. Tez, Covid-19 pandemisi ve karantinalar nedeniyle günlük yaşamdaki değişikliklerden etkilenmiştir. Gerçek enerji tüketiminde bina sakininin rolünün anlaşılması için, farklı hanehalkı tipolojileri pandemi sonrası günlük yaşama uygun olarak modellenmiş ve analiz edilmiştir.

Anahtar Kelimeler: Kullanıcı Davranışları, İnsan Bina Etkileşimi, Kullanıcı Şemaları, Bina Performans Simülasyonu, Hanehalkı Tipolojileri

To my family,

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LIST OF ABBREVIATIONS

AC	Air Conditioning
SBEM	Simplified Building Energy Model
BPS	Building Performance Simulation
DNAS	Driver, Need, Action, System
EBC	Energy in Buildings and Communities Program
EU	Europion Union
HBI	Human Building Interaction
HVAC	Heating, Ventilating and Air Conditioning
IEA	International Energy Agency
IT	Information Technologies
LBNL	Lawrence Berkeley National Laboratory
obXML	occupancy behavior eXtensible Markup Language
obFMU	occupancy behavior Functional Mockup Unit
US	United States

CHAPTER 1

INTRODUCTION

1.1 The Motivation of Thesis

Since the modern people spend most of their time indoors, undoubtfully the fundamental aim of the buildings is to generate a comfortable living and working environment for humans. The most significant measure for a qualified shelter is a suitable interior environment that affects the well-being, productivity, and comfort of the occupants.[1] In this regard, the architects and engineers are responsible for ensuring a certain comfort level to the occupants by using various environmental and mechanical systems that mainly rely on energy resources.

Globally, the energy consumption of the building industry is constantly increasing, and more over one-fifth of total supplied energy consumption is accounted by the building industry.[2] According to International Energy Agency Annex 53, there are mainly six causes that affect the energy use of a building: climate, building envelop characteristics, building serves and energy system characteristics, building operation and maintenance, occupant activities and behavior, the provided indoor environmental quality.[3]

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[1] International Energy Agency and Technology Collaboration Programme, *Indoor Air Quality Design and Control in Low-Energy Residential Buildings*, 2020.
[2] Da Yan, Tianzhen Hong, Bing Dong, Ardeshir Mahdavi, et al., "IEA EBC Annex 66: Definition and Simulation of Occupant Behavior in Buildings," *Energy and Buildings*, vol. 156, 2017, 2, https://doi.org/10.1016/j.enbuild.2017.09.084.
[3] Energy in Buildings and Communities Programme (EBC), "Final Report Annex 53. Total Energy Use in Buildings Analysis and Evaluation Methods," *International Energy Agency Programme on Energy in Buildings and Communities*, 2016, 7.

Building performance simulations (BPS) evaluate the driver factors to predict building energy consumption. BPS is utilized in architectural design to generate ecologically responsible design solutions and reveal interactions between the building and its occupants, HVAC systems, and outdoor temperature.[4] BPS is influenced by a number of performance and user-related factors, including building characteristics, environmental control systems, weather conditions, occupants, internal loads, operation strategies and schedules.[5] An accurate simulation depends on the quantity and quality of input parameters and a precise building model.

One of the primary purposes of building performance calculations is to predict the energy performance of a building before it is in use. However, there is usually a difference between the predicted and measured performance of the building, which is defined as the performance gap. Differences in occupancy behavior are accepted as the fundamental cause of the performance gap. In fact, different occupant behavior can create a 12% variation from predicted energy usage.[6] This study focuses on the occupancy that is considered the root cause of the uncertainty in building performance.

Occupant behavior is a multidisciplinary research topic related to social and behavioral science, building science, sensing and control technologies, computing science, and data science.[7] The desire of the occupants to achieve comfort within their environment is the primary reason behind the energy-related occupant behavior. Occupants may have an impact upon the indoor environment to fulfill their

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[4] J. A. Clarke and J. L.M. Hensen, "Integrated Building Performance Simulation: Progress, Prospects and Requirements," *Building and Environment* 91 (2015): 294–306, https://doi.org/10.1016/j.buildenv.2015.04.002.
[5] Martin Arthur Fischer, "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective," no. January (2007): 43.
[6] Lina La Fleur, Bahram Moshfegh, and Patrik Rohdin, "Measured and Predicted Energy Use and Indoor Climate before and after a Major Renovation of an Apartment Building in Sweden," *Energy and Buildings* 146 (2017): 98–110, https://doi.org/10.1016/j.enbuild.2017.04.042.
[7] Tianzhen Hong, Sarah C. Taylor-Lange, Simona D'Oca, Da Yan, et al., "Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings," *Energy and Buildings* 116 (2016): 694–702, https://doi.org/10.1016/j.enbuild.2015.11.052.

comfort conditions by changing thermostat set point, lighting on/of control, window open/close control, HVAC on/off control, and pulling up/down blinds.[8] Therefore, analyzing user behaviors increases the possibility of providing occupant comfort. The limited knowledge of occupant behavior leads to unreliable and overly simplified building performance predictions, differences in building design optimization, and inaccurate building energy simulation.[9]

Integration of occupant schedules with BPS enables to simulate energy-related occupancy behavior in buildings and decreases the performance gap between predicted and measured energy consumption.[10] Occupant presence, movement and action models are the human-building interaction parameters for simulations. The number of occupants is determined in the presence model. The movement model represents the location of occupants and their movement between different zones. Finally, the action model analysis the interaction between the occupant and building systems such as lighting and HVAC.[11] The thesis studies the occupancy models that have greater impact on building performance.

Occupancy has various methods for modeling and simulation. Statistical occupancy schedules are based on observation and data collection from real-life studies.[12] These schedules are the early examples of occupancy schedules represent an unrealistic result compared to real life due to ignorance of the individual differences. However, the most common and user-friendly interface occurs in this type of schedules. Stochastic models represent unexpected changes in behavior across time depending

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[8] Mohamed M. Ouf, William O'Brien, and H. Burak Gunay, "Improving Occupant-Related Features in Building Performance Simulation Tools," *Building Simulation* 11, no. 4 (2018): 803–17, https://doi.org/10.1007/s12273-018-0443-y.
[9] Yan, Hong, Dong, Mahdavi, et al., "IEA EBC Annex 66: Definition and Simulation of Occupant Behavior in Buildings."
[10] Hong, Taylor-Lange, D'Oca, Yan, et al., "Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings."
[11] Seddigheh Norouziasl, Amirhosein Jafari, and Yimin Zhu, "Modeling and Simulation of Energy-Related Human-Building Interaction : A Systematic Review," *Journal of Building Engineering* 44, no. February (2021): 4–20, https://doi.org/10.1016/j.jobe.2021.102928.
[12] Ibid.

on mathematical models. Models based on machine learning examine historical trends in data received from various monitoring systems in order to extract energy-related patterns of occupants. Recent research has focused on agent-based models to examine human-building interaction. "The purpose of the agent-based modeling is to mimic a real-world occupant: an autonomous agent that interacts with both its environment and other agents, and makes behavior decisions based on the level of its thermal comfort." [13]

The building performance simulation and occupancy researchers often study offices as the case environment due to more defined and predictable user profiles than residential or other building types. However, due to the Covid pandemic, home working environments increased, and the energy consumption of residential buildings was substantially affected. Globalization of work environments, developments in digital infrastructure, and the growth of the service industry also support home working environments. The thesis utilizes the present situation of residential buildings and home office environments that generates a current research area for occupancy and energy consumption.

This study aims to investigate the impact of occupancy on energy consumption of residential buildings to obtain data about energy use during Covid pandemic conditions and in the home office setting. In order to construct the case study, the thesis examines TUIK household data. Various occupancy, equipment, and lighting schedules are produced for the primary four types of households. As a result, the thesis incorporates the occupancy, equipment, and lighting schedules into simulations to observe their effect on the predicted energy consumption of different households in post-pandemic conditions.

[13] Yixing Chen, Xin Liang, Tianzhen Hong, and Xuan Luo, "Simulation and Visualization of Energy-Related Occupant Behavior in Office Buildings," *Building Simulation* 10, no. 6 (2017): 1, https://doi.org/10.1007/s12273-017-0355-2.

1.2 Research Questions

The study aims to explore the effect of occupancy, equipment, and lighting schedules produced in reference to the occupancy data and different household typologies on building performance simulations. In this context, this thesis addresses the following research questions.

- To what extent has the occupants' post-pandemic daily routines changed the energy consumption of residential buildings?
    - How did post-pandemic conditions change the energy-related routines of the occupants?
    - How does the size of the dwellings affect the energy consumption per area?
    - How does the number of household members affect the energy consumption per person?
    - What is the relationship between heating, appliance, and lighting energy use according to the type of household?
    - How did teleworking and distance education influence the energy consumption in dwellings?
    - How can the role of occupant behavior in energy consumption be understood by evaluating the specific household types and building characteristics?

1.3 Structure of the Thesis

The thesis is composed of five main chapters. The current introduction chapter briefly explains the problems, aim, and motivation of the study together with the research questions.

Chapter two represents the literature review of the research. In order to better understand the importance of the study; energy use in the building sector, building performance simulation, predicted and measured energy use, and energy-related human-building interaction are explained with references to the literature. The chapter also represents the effects of the Covid-19 pandemic in energy use behaviors and indoor usage habits by the studies in the literature. The current condition of daily residential life is depicted according to post-pandemic conditions.

Chapter three describes the main driver of the study. The chapter starts with the definition of occupancy and occupancy behaviors and explains the multidisciplinarity of the subject. The data collection methods and types of the occupancy schedules are represented in the second part of chapter three. The simulation of the occupancy schedules, techniques, integration with building performance simulations, and limitations are described in the final section.

Chapter four includes the case studies for the research. The Turkish Statistical Institute (TUIK) household study is analyzed for the determining of the household types. The selection of the focus group and the methodology of the study are reviewed at the beginning of the chapter. Focus group interview content and accordingly the process of formation of the schedules are explained in detail. The main part of the chapter four clarifies the four household case studies. Finally, the chapter expounds on the results of the performance simulations of the case studies. Firstly, heating, appliance, and lighting energy use data for each case is discussed through the graphs. Then, the comparative analysis is made between household cases, and the research questions are revisited in order to evaluate the results.

Finally, in the last chapter, the study is concluded with an evaluation. The outcomes of the research are mentioned. Limitation of the study and the future suggestions are represented to demonstrate the potential of study in the final part of the chapter and the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Energy Use in Building Sector

People spend a significant part of their lives indoors depending on mechanical ventilation, heating systems, appliances, and lightings, and thereby buildings are one of the most important end-use industry. In the European Union (E.U.) and the United States (U.S.), over 20% of overall energy consumption is consumed by buildings.[14] Between 1980 and 2010, the ratio of building energy consumption to total energy consumption increased from 33.7% to 41.1% in the U.S.[15] There are several reasons behind this increase; population growth, global warming, request for better quality interior environments, a growing number of single-person livings and increase the use of indoors.[16] Also, the growing use of electrical appliances may be one of the reasons. However, according to researches, energy consumption is not significantly affected due to the increasing efficiency of these appliances.

Residential buildings account for almost two-thirds of all building energy use.[17] In the residential sector, space heating is the most significant end-use with 67%, followed by water heating with 13%, electrical appliances with 11%, cooking with 6%, and lighting with 2%. The minor portion belongs to cooling (air conditioning)

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[14] Yan, Hong, Dong, Mahdavi, et al., “IEA EBC Annex 66: Definition and Simulation of Occupant Behavior in Buildings.”
[15] Xiaodong Cao, Xilei Dai, and Junjie Liu, “Building Energy-Consumption Status Worldwide and the State-of-the-Art Technologies for Zero-Energy Buildings during the Past Decade,” *Energy and Buildings* 128, no. 2012 (2016): 198–213, https://doi.org/10.1016/j.enbuild.2016.06.089.
[16] Ibid.
[17] Bosseboeuf et al., “Energy Efficiency Trends and Policies in the Household and Tertiary Sectors,” no. June (2015): 97.

with %0.5.[18] Space heating and cooling is the most dominating energy end-use in the services sector, after electrical appliances, water heating, and lighting.[19]

Kavousian, Rajagopaj and Fischer classify the variables that affect energy consumption into four categories. [20] The first one is external conditions that express the location of the residence and the weather conditions. The location information clarifies about 46% variability in consumption. The second category is physical characteristics of dwelling that include size and age of the residence, type of building (apartment, detached house, etc.), and ownership status (rented or owned). The size of the house is the most important aspect among the building characteristics. Thirdly, appliance and electronics stock is another group that affects energy consumption. Refrigerators and air conditioners are the most energy-intensive equipment in the houses. The last category is occupants that influence consumption with occupancy level, occupant behavior and occupant socio-economic status. Occupant age shows a relationship with energy consumption. Occupants older than 55 are more conscious about energy usage, and occupants between 19 and 35 are mostly employees and not using the house during day time. Therefore these groups are the least energy consumers. In general, families with children who work full-time and have a high level of education are more efficient than families without children or families with retirees or unemployed members.[21] Overall, external conditions and building physical characteristics have a greater impact on residential energy use than other factors such as occupants. Similarly, research on Dutch housing shows that building

[18] Ibid.
[19] Cao, Dai, and Liu, "Building Energy-Consumption Status Worldwide and the State-of-the-Art Technologies for Zero-Energy Buildings during the Past Decade."
[20] Amir Kavousian, Ram Rajagopal, and Martin Fischer, "Determinants of Residential Electricity Consumption: Using Smart Meter Data to Examine the Effect of Climate, Building Characteristics, Appliance Stock, and Occupants' Behavior," *Energy* 55 (2013): 184–94, https://doi.org/10.1016/j.energy.2013.03.086.
[21] Amir Kavousian, Ram Rajagopal, and Martin Fischer, "Ranking Appliance Energy Efficiency in Households: Utilizing Smart Meter Data and Energy Efficiency Frontiers to Estimate and Identify the Determinants of Appliance Energy Efficiency in Residential Buildings," *Energy and Buildings* 99 (2015): 220–30, https://doi.org/10.1016/j.enbuild.2015.03.052.

characteristics account for 42% of the variation in energy use, while tenant behavior accounts for 4.2%.[22]

After the global oil crisis in the 70's, many countries started to establish energy efficiency measures. Efficiency is defined as "doing more using less"[23] and has become even more critical with climate change. Since the buildings are the major energy consumers in all sectors, adequately designed, constructed, and operated buildings provide remarkable energy savings. Since 2000, space heating energy use has reduced in the most E.U. countries in consequence of developments in energy efficiency.[24]

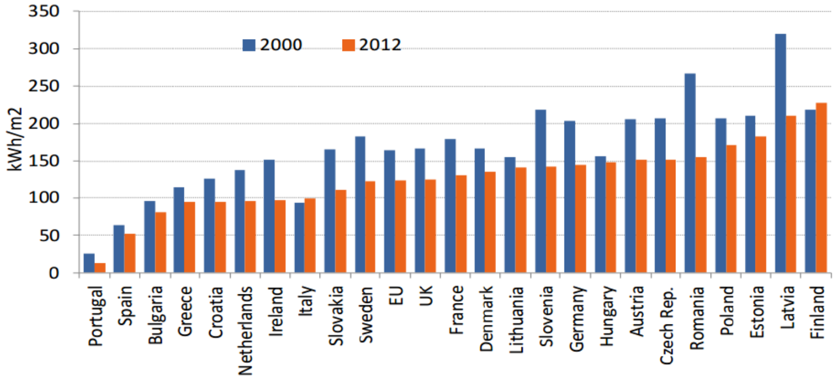

Figure 2.1 Space Heating Energy Usage per m² in E.U. Countries[25]

Existing buildings constitute a large portion of the built environment in E.U. Energy saving in space heating through improvements in building envelopes and heating equipment is a priority for existing buildings, especially in the residential sector.[26]

[22] Olivia Guerra Santin, Laure Itard, and Henk Visscher, "The Effect of Occupancy and Building Characteristics on Energy Use for Space and Water Heating in Dutch Residential Stock," *Energy and Buildings* 41, no. 11 (2009): 1223–32, https://doi.org/10.1016/j.enbuild.2009.07.002.
[23] Kavousian, Rajagopal, and Fischer, "Ranking Appliance Energy Efficiency in Households: Utilizing Smart Meter Data and Energy Efficiency Frontiers to Estimate and Identify the Determinants of Appliance Energy Efficiency in Residential Buildings."
[24] Cao, Dai, and Liu, "Building Energy-Consumption Status Worldwide and the State-of-the-Art Technologies for Zero-Energy Buildings during the Past Decade."
[25] Ibid.
[26] Ibid.

New buildings theoretically consume 40% less energy than buildings constructed before 1990, according to building regulations.[27] However, these new buildings generate only 23% of the total built environment in E.U. and remain a limited portion of the stock. For countries having a significant number of new construction and rapid urbanization, it is more efficient to improve energy efficiency in new construction.[28]

There are some methods that can be adapted to daily life to increase energy efficiency. The most effective change is using energy from renewable sources for space and water heating. Similarly, wall insulation, efficient light bulbs, double panel windows, and heater timers lead to higher efficiency. Owned dwellings are commonly more efficient since the investment in energy-saving features (wall insulation, heater timers, etc.) Occupied houses during the day represent less efficiency due to the increased use of appliances.[29] People must become conscious of their energy consumption and be informed about the outcome to modify their energy behavior.[30] Architects are responsible for developing holistic design strategies for the energy-efficient living. Various elements should be considered while developing design strategies, including local site and climate conditions, building types, energy costs, projected climate change tendency, system functioning, and techno-economics.[31] Overall, it is a complicated issue that addresses both energy and cost efficiency, as well as being environmentally friendly and energy balanced while also offering a comfortable living environment.

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[27] Bosseboeuf et al., "Energy Efficiency Trends and Policies in the Household and Tertiary Sectors."
[28] Ibid.
[29] Kavousian, Rajagopal, and Fischer, "Ranking Appliance Energy Efficiency in Households: Utilizing Smart Meter Data and Energy Efficiency Frontiers to Estimate and Identify the Determinants of Appliance Energy Efficiency in Residential Buildings."
[30] Bosseboeuf et al., "Energy Efficiency Trends and Policies in the Household and Tertiary Sectors."
[31] Cao, Dai, and Liu, "Building Energy-Consumption Status Worldwide and the State-of-the-Art Technologies for Zero-Energy Buildings during the Past Decade."

2.2 Building Performance Simulation

In recent times, green buildings have become popular with increasing attention to environmental awareness and sustainable design developments. The energy needs of building energy systems such as building space, HVAC systems, and lighting systems directly impact the operating expenses and an indirect impact on the environment.[32] Since the buildings are responsible for a considerable amount of energy usage in all sectors, it is necessary to develop strategies to reduce energy consumption and support sustainability within a building. As a result, building performance simulations (BPS) not only reveals interactions between the building and its inhabitants, HVAC systems, and the outdoor temperature, but it is also used in architectural design to produce ecologically responsible design solutions.[33]

Energy efficiency in buildings requires the integrity of multiple disciplines, such as architecture, civil, mechanical, and electrical engineering.[34] Building performance simulation is the expected value to evaluate the efficiency of buildings for these disciplines. The complexity of the simulation programs has created difficulties for architects to use until the last decades. User-friendly interfaces emerged with the increase in the variety of the BPS programs, and architects have been involved in energy simulation processes. For instance, current development on EnergyPlus (a BPS program) interfaces is encouraging, and it is expected that appropriate ease of use and functionality will be available in the near future.[35] User-friendly interfaces do not make energy analysis accessible to everyone; knowledge of program

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[32] V S K V Harish and Arun Kumar, "A Review on Modeling and Simulation of Building Energy Systems," *Renewable and Sustainable Energy Reviews* 56 (2016): 1272–92, https://doi.org/10.1016/j.rser.2015.12.040.
[33] Clarke and Hensen, "Integrated Building Performance Simulation: Progress, Prospects and Requirements."
[34] Kristoffer Negendahl, "Building Performance Simulation in the Early Design Stage: An Introduction to Integrated Dynamic Models," *Automation in Construction* 54 (2015): 39–53, https://doi.org/10.1016/j.autcon.2015.03.002.
[35] Fischer, "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective."

restrictions and awareness of thermal processes are required for the generation and interpretation of realistic and credible simulation results.[36] Clarke and Hansen summarize the developments in BPS as follow:

> "In the early days of building performance simulation, users were likely to be building physicists or building services engineers concerned to evaluate the impact of a limited number of energy efficiency measures and/or size HVAC equipment. Contemporary BPS application is driven by concerns such as energy demand reduction, climate change mitigation, environmental protection, fossil fuel replacement, security of supply and improved living standards. This situation has given rise to several distinct needs: support for diverse user types and applications; upward and downward extension of the application scale; the linking of energy, environment, wellbeing and productivity; the imposition of uncertainty and risk; consideration of life cycle performance; support for both design and policy objectives; and the addition of new technical domains such as micro-generation, micro-grids and demand management/response. In short, BPS has become much more than a building design support tool."[37]

Energy performance simulation programs are valuable tools for analyzing a building's energy performance, indoor environmental quality, and thermal comfort during its life cycle. There are various BPS tools available today, and they differ in many respects, including their thermodynamic models, graphical user interfaces, life-cycle applicability, the purpose of usage, and the capacity to interchange data with other software programs.[38] Current developments in computing power,

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[36] Ibid.
[37] Clarke and Hensen, “Integrated Building Performance Simulation: Progress, Prospects and Requirements,” 297.
[38] Fischer, “Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective.”

algorithms, and physical data enable the simulation of physical processes at various degrees of detail and time spans.[39]

Building performance simulation is not an easy task since it is affected by several parameters related to the building characteristics, HVAC systems, weather, occupants, internal loads, operating strategies and schedules, and simulation specific parameters (Figure 2.2 and 2.3).[40] There is some significant factor that affects the precision of BPS results, such as; using the proper simulation engine according to the user's experience, the proper hardware system to run the simulation, and the suitable level of modeling. Also, an accurate simulation depends on the quantity and quality of input parameters as much as a precise building model. The engine performs a simulation using the input files, and as a consequence, it produces its output to one or maybe more output files. While the output files include simulation results, they also contain data about the simulation run, warnings, or supplementary information for evaluating the input.[41] The simulation result is a simplification of reality and a method of calculating the approximate value of building performance.

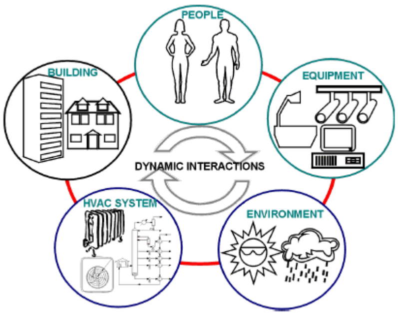

Figure 2.2 Interacting Actors in a Building[42]

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[39] Jan L. M. Hensen, "Towards More Effective Use of Building Energy Performance Simulation in Design Center for Buildings and Systems," *Developments in Design & Decision Support Systems in Architecture and Urban Planning*, no. Kusuda 2001 (2004): 291–306.
[40] Fischer, "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective."
[41] Ibid.
[42] Ibid.

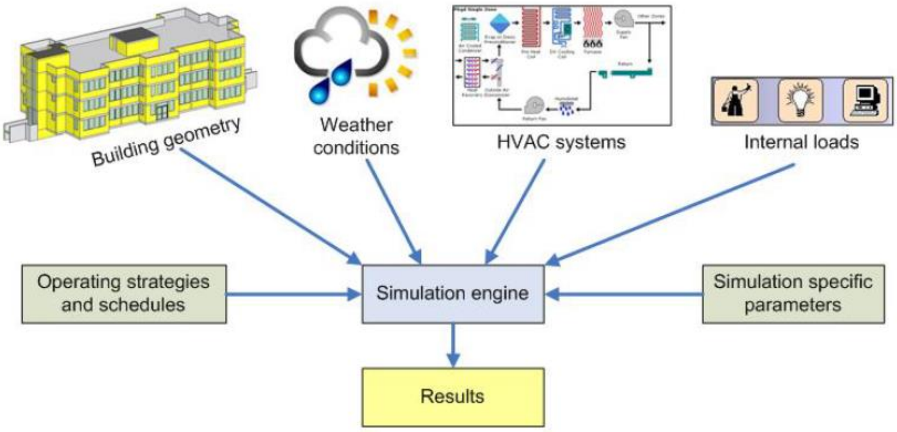

Figure 2.3 Building Simulation Parameters[43]

Although simulation has become commonly used in building design, it does not originate design solutions directly. Rather than, it produces feedback about the performance of the design option, and it assists user comprehension of complicated systems.[44] In today's design projects, the principal uses of building simulation are analytical rather than design-oriented.

Integration of BPS tool to architectural design developed after a number of experiences. Initially, the final building design simulated to decide which building energy systems and sizes will be used. Since this simulation only represents analytical information about building performance, it did not support any other design alternatives. Despite the fact that, design decisions have a major effect in the early design stages, BPS was seldom utilized to support the tasks during the early design process.[45] In order to increase the utilization of building performance modeling during the early design phase, developers investigated new, advanced models and applications that satisfy the demands of the architectural, engineering, and construction sectors. The production and selection of design choices during the

[43] Ibid.
[44] Clarke and Hensen, "Integrated Building Performance Simulation: Progress, Prospects and Requirements."
[45] Hensen, "Towards More Effective Use of Building Energy Performance Simulation in Design Center for Buildings and Systems."

early design stages have a significant influence and effect throughout the building life cycle.[46]

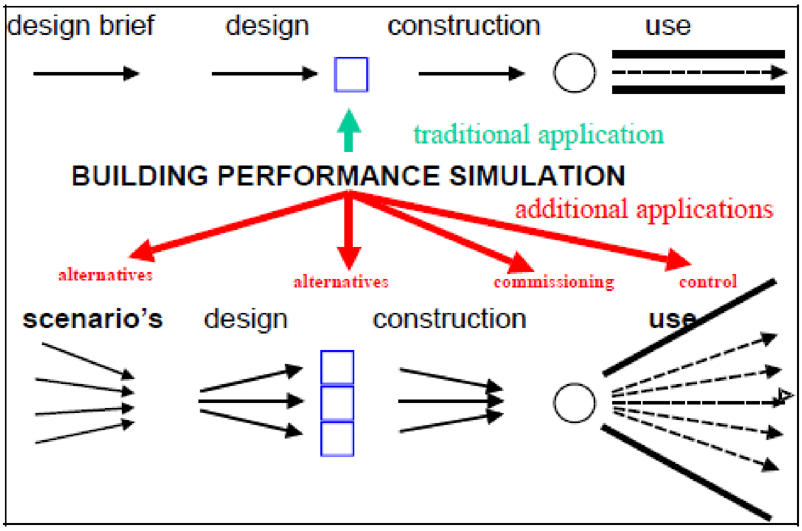

Figure 2.4 Expanding the Scope of BPS[47]

However, recent advancements determine a larger use of BPS throughout all phases of a building's life cycle. Integration BPS to each step of building design, construction, and usage generate a wider range of alternates. Rather than projecting absolute energy consumption levels, the strength of performance modeling nowadays is the comparison of several design choices.[48] In general, BPS improves comprehension of how a given building performs according to specified criteria and allows for comparisons of several design choices.[49]

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46 Ibid.
47 Fischer, "Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective."
48 Ibid.
49 Ibid.

2.3 Predicted and Measured Energy Use

Energy efficiency is a significant and current concept in the construction industry. Buildings that are more energy efficient are becoming increasingly desirable. Consequently, it has become essential to ensure that the energy performance estimation at the design stage is achieved while the building is in operation.[50] The difference between the predicted and measured performance of the building is defined as a performance gap. Although the performance gap mostly refers to energy consumption, there are other discrepancies between predicted and measured performance, such as indoor air quality, lighting levels, acoustic performance, and thermal comfort. Researches show that the actual energy consumption can be up to 2.5 times the calculated energy consumption.[51]

The performance gap terms firstly appeared in the mid-1990s to discuss the discrepancies between predicting and measuring a building's energy performance, including sub-systems, occupancy behavior, climate and weather variables, and control settings.[52] Since then, it has been a current research subject due to uncertainties multiplicity of parameters.

De Wilde explains the type of performance gap in the literature into three groups. The first type is the difference between the predicted and the measured building performance that is commonly accepted as the definition of the performance gap in the literature. The second type of gap is the difference between machine learning and

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[50] Anna Carolina Menezes, Andrew Cripps, Dino Bouchlaghem, and Richard Buswell, "Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap," *Applied Energy* 97 (2012): 355–64, https://doi.org/10.1016/j.apenergy.2011.11.075.
[51] Pieter De Wilde, "The Gap between Predicted and Measured Energy Performance of Buildings: A Framework for Investigation," *Automation in Construction* 41 (2014): 40–49, https://doi.org/10.1016/j.autcon.2014.02.009.
[52] Ibid.

calculated performance. The last type is the difference between the predicted performance and regulatory certificates.[53]

The main reason for the performance gap is the selected method and parameters of the energy consumption calculations. The building performance simulations contain multiple input parameters. Defining the reason for the performance gap is compelling since all parameters are processed at the same time. Some of these parameters are nonmeasurable in the design stage, such as occupancy behavior, equipment schedule, and lighting level. It is commonly accepted that variances in occupancy behavior cause discrepancies in predicted performance. Different user behavior can create a 12% variation from predicted energy usage.[54] Numerical simulation errors also affect the performance gap, although to a minor extent.

The demand by regulations to produce more energy efficient buildings causes optimistic predictions. 80% of the simulations are only utilized to gain green building certification.[55] Consequently, the regulation about certification promotes the performance gap.

De Wilde categorizes the causes for the performance gap into three groups. The first cause belongs to the design phase, the second cause is grounded in the construction phase, and the last cause is engaged in the operational phase.[56] Uncertainties in the design stage are one of the main reasons for the performance gap. The expected performance targets should be clarified together with the client and design team. Although the architect ensures the performance targets, lack of attention to buildability, simplicity, sequencing of the construction process, or lack of appropriate detail could cause the performance gap. The calculation of performance

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[53] Ibid.
[54] La Fleur, Moshfegh, and Rohdin, "Measured and Predicted Energy Use and Indoor Climate before and after a Major Renovation of an Apartment Building in Sweden."
[55] Agency and Programme, *Indoor Air Quality Design and Control in Low-Energy Residential Buildings*.
[56] De Wilde, "The Gap between Predicted and Measured Energy Performance of Buildings: A Framework for Investigation."

in simulations requires evaluating various parameters during the design process; consequently, this creates another layer of complexity in the design phase. Even though the model is accurately and consistently constructed in simulations, the analyst capability still might engender the performance gap. The variation in weather conditions, occupancy behavior, appliance schedule, and internal heat gain create uncertainty during the design stage.[57] The second group for causes in performance gap arises in the construction phase. The specification is the determiner for the quality of material and techniques in building. Building quality is usually not adequate to specification, especially in terms of insulation and airtightness. Unspecified details generate a risk for thermal bridges that affect the performance of the building. Due to construction containing many layers in itself, it is difficult to determine which layer is inappropriate to the specifications. Currently, there is a concern about proper testing to assess the performance of new structures once they are in use.[58] The final stage for the performance gap is the operational phase. Occupant behavior frequently differs from the predictions established during the design stage that influence appliance loads and internal gain values. As mentioned previously, this is generally considered the primary cause of the performance gap. Also, technological progress affects building performance. IT related appliances usually require more electricity than predicted.[59]

The primary reasons for the performance gap might emerge in the design stage as well as construction and operation stages. Improving management of the building design, construction, and operation processes can minimize errors during each process. All professions engaged in a construction project, such as architects,

[57] Ibid.
[58] Ibid.
[59] Ibid.

engineers, clients, consultants, builders, and facility managers, should work together to bridge the performance gap.[60]

Bridging the performance gap is significant in order to generate buildings that are resilient to change, perform well over time, and that are designed to respond to the changing condition of occupancy and climate. Model affirmation, advanced data set for predictions, updating industry practice, and better forecasting are the fundamental approaches that bridge the performance gap.[61]

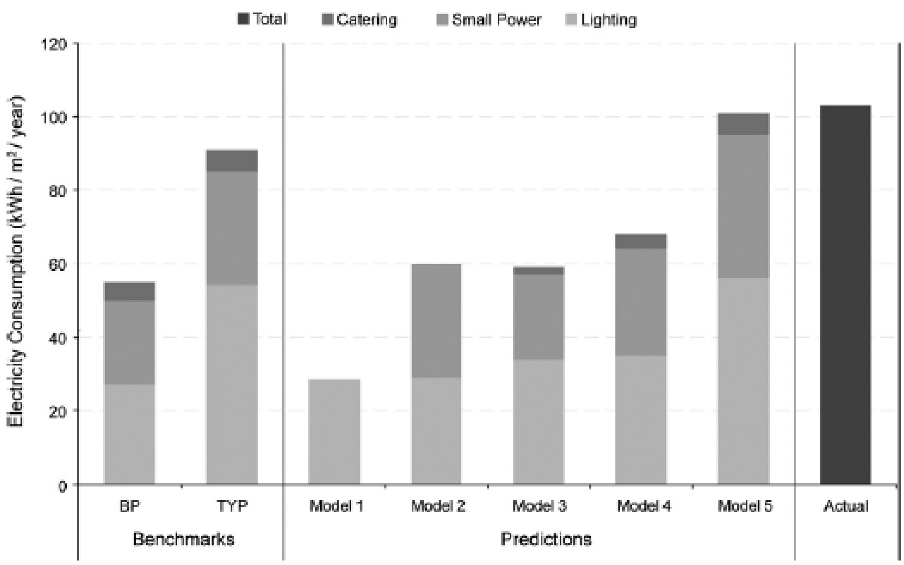

Figure 2.5 Comparision of Predicted and Actual Electricity Consumption[62]

It is challenging to obtain an accurate depiction of actual building operations due to the complexity of the built environment and the independent parameters. In reality, many of these parameters are either unattainable or unmeasurable. Building performance model calibration evaluates simulation outputs with the measured data

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[60] Xing Shi, Binghui Si, Jiangshan Zhao, Zhichao Tian, et al., "Magnitude, Causes, and Solutions of the Performance Gap of Buildings: A Review," *Sustainability (Switzerland)* 11, no. 3 (2019): 1–21, https://doi.org/10.3390/su11030937.
[61] De Wilde, "The Gap between Predicted and Measured Energy Performance of Buildings: A Framework for Investigation."
[62] Menezes, Cripps, Bouchlaghem, and Buswell, "Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap."

to decrease the discrepancies between predicted and actual data. Consequently, the calibration increases the efficiency and reliability of predicted outcomes.[63]

Menezes et al. compared five different predicted electricity models with actual electricity consumptions of an office building in London in Figure 2.5. Variables of the models are lighting, occupancy and appliance, and cooking schedules. In predicted model 1, the lighting schedule is derived from design specification, and SBEM (Simplified Building Energy Model) standard occupancy schedule is used as input. Appliance and cooking loads are ignored. The simulation result is 1/3 of the actual consumption. Model 2 also includes the consumption of the appliances in simulation; as a result, predicted consumption is doubled. Model 3 is calibrated in terms of lighting and appliances. Measured data replaced with predicted, and results show that actual lighting load is higher and appliance load is lower than expected. In predicted model 4, lighting, appliances, and cooking loads are replaced with advanced measured data. Consumption increased by almost 15% in the total electricity consumption. Lastly, in model 5, actual occupancy load is used in simulation instead of the SBEM model. Consequently, the predicted electricity usage is within 3% of the actual use of the building when it was in use.[64]

2.4 Energy Related Human-Building Interaction

One of the fundamental purposes of buildings is creating comfortable environments for humans. Occupants interact with the building and its elements to ensure their comfort needs, and this cooperation is defined as the human-building interaction

[63] Daniel Coakley, Paul Raftery, and Marcus Keane, "A Review of Methods to Match Building Energy Simulation Models to Measured Data," *Renewable and Sustainable Energy Reviews* 37 (2014): 123–41, https://doi.org/10.1016/j.rser.2014.05.007.
[64] Menezes, Cripps, Bouchlaghem, and Buswell, "Predicted vs. Actual Energy Performance of Non-Domestic Buildings: Using Post-Occupancy Evaluation Data to Reduce the Performance Gap."

(HBI) in the literature. Bill Hiller introduces the HBI in his book "Space is the Machine":

> "Built environments are a construction of physical elements that create and protect a space. Each of these two aspects, the physical and the spatial, carry a social value: the former by the shaping and decoration of elements (with functional or cultural significance), and the latter by providing spatial patterning of activities and relationships. Designing Human-Building Interaction, in that perspective, consists of providing interactive opportunities for the people to shape the physical, spatial, and social impacts of their built environment."[65]

Although the interaction is gathered under three topics (physical, spatial, and social), they are also interconnected. For instance, the decision of turning on lighting to provide visual comfort in a shared space includes physical interaction as well as social interaction for the occupants in the same space. Research has found individual thermoregulation variances among individuals. Due to individualized comfort requests, HBI has become more significant in current designs.[66] While HBI provides individual control over building systems, having this control as an individual has value by itself.[67]

Occupant behaviors affect building performance and indoor environmental quality through HBI. Occupants interact with the building control systems by changing thermostat set point, lighting on/of control, window open/close control, HVAC

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[65] Bill Hiller, *Space Is the Machine* (London: Space Syntax, 2007). as quoted in Hamed S Alavi, Elizabeth F Churchill, Mikael Wiberg, Denis Lalanne, et al., "Introduction to Human-Building Interaction (HBI): Interfacing HCI with Architecture and Urban Design," *ACM Transactions on Computer-Human Interaction* 26, no. 2 (April 28, 2019): 1–10, https://doi.org/10.1145/3309714.
[66] Tianzhen Hong, Chien fei Chen, Zhe Wang, and Xiaojing Xu, "Linking Human-Building Interactions in Shared Offices with Personality Traits," *Building and Environment* 170, no. September 2019 (2020): 1–10, https://doi.org/10.1016/j.buildenv.2019.106602.
[67] Jörn Von Grabe, "How Do Occupants Decide Their Interactions with the Building? From Qualitative Data to a Psychological Framework of Human-Building-Interaction," *Energy Research and Social Science* 14 (2016): 46–60, https://doi.org/10.1016/j.erss.2016.01.002.

on/off control, and pulling up/down blinds to provide thermal comfort in an indoor space.[68] For example, opening or closing the window generates the possibility to control temperature, light, air quality, acoustics, privacy, and social connections between inside and outside.[69] A sophisticated HBI system improves occupant productivity, comfort, and health while reducing energy consumption in buildings. Hong et al. study the most influential factors that affect the HBI behaviors of occupants. According to the research, the three most significant aspects that determine HBI behaviors are the country, control feature accessibility, and group dynamics.[70] In addition to these three aspects, gender and age are among the factors influencing HBI.

The study shows that only behavioral differences can reduce energy usage between 9 and 18% in an office building.[71] Predicting the behavioral factor in the design stage increase the reliability of performance calculations. However, behavior models are based on the simplification of reality. Stochastic nature of human results models that are far from realistic behaviors.[72] When an uncomfortably or a need for privacy occurs, there are multiple behavioral acts to optimize the local environment. Discomfort caused by warm indoor can be relieved by the opening window to reduce room temperature, closing blinds to decrease internal radiation, switching on AC to increase air movement, or adapting clothing level to feel comfortable.[73] All of these

[68] Hong, Chen, Wang, and Xu, "Linking Human-Building Interactions in Shared Offices with Personality Traits."
[69] Alavi, Churchill, Wiberg, Lalanne, et al., "Introduction to Human-Building Interaction (HBI): Interfacing HCI with Architecture and Urban Design."
[70] Hong, Chen, Wang, and Xu, "Linking Human-Building Interactions in Shared Offices with Personality Traits."
[71] Esmat Zaidan, Ali Ghofrani, and Ernest Dokaj, "Analysis of Human-Building Interactions in Office Environments : To What Extent Energy Saving Boundaries Can Be Displaced?" 9, no. August (2021): 1–14, https://doi.org/10.3389/fenrg.2021.715478.
[72] Agency and Programme, *Indoor Air Quality Design and Control in Low-Energy Residential Buildings*.
[73] Von Grabe, "How Do Occupants Decide Their Interactions with the Building? From Qualitative Data to a Psychological Framework of Human-Building-Interaction."

behaviors have an impact on building energy usage and must be evaluated in order to optimize the performance of buildings.

2.5 Behavioral Pattern of Covid-19

The World Health Organization announced that Coranavirus disease (Covid-19) is a global pandemic in March 2020.[74] Researchers have increasingly started to analyze the impact of the Covid-19 pandemic on health, economy, and social well-being. The pandemic conditions have changed the lifestyle and daily habits of the people. Many countries imposed extremely stringent lockdown restrictions for a period of time in 2020, and it has been suggested to stay at home as possible. The lockdowns change the occupancy schedules of the residential and non-residential buildings due to the shift in time spent in the houses. The dwellings become the center of daily life; "an office for those teleworking, a nursery or classroom for children and pupils, and a hub for online shopping or downloading entertainment for many."[75] As a result, people use computers, laptops, lighting, and other appliances at home that would typically have been used in their offices and schools. Furthermore, the limited availability of outdoor entertainment activities leads people to seek alternatives in their homes, often resulting in a significant increase in energy consumption.[76] Consequently, building energy consumption is directly affected by the pandemic occupancy schedules.

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[74] World Health Organization. (n.d.). *Coronavirus disease (covid-19) - events as they happen*. Retrieved January 27, 2022, from https://www.who.int/emergencies/diseases/novel-coronavirus-2019/events-as-they-happen

[75] Marta Monzón-Chavarrías, Silvia Guillén-Lambea, Sergio García-Pérez, Antonio Luis Montealegre-Gracia, et al., "Heating Energy Consumption and Environmental Implications Due to the Change in Daily Habits in Residential Buildings Derived from COVID-19 Crisis: The Case of Barcelona, Spain," *Sustainability (Switzerland)* 13, no. 2 (2021): 2, https://doi.org/10.3390/su13020918.

[76] Ahmed Abdeen, Farzam Kharvari, William O'Brien, and Burak Gunay, "The Impact of the COVID-19 on Households' Hourly Electricity Consumption in Canada," *Energy and Buildings* 250 (2021): 1–17, https://doi.org/10.1016/j.enbuild.2021.111280.

Besides stresses inherent in the illness itself, surveys have shown that more people suffered from depressive symptoms during Covid-19 lockdowns due to the effect of home confinement on mental and psychological health.[77] "Simultaneously, the fear and uncertainty instilled by the perceived health risk and economic ramifications of the pandemic have increased insomnia, anxiety, depression, and suicide rates."[78] In order to overcome the negative effect of the Covid-19, people satisfy their entertainment needs at home by owning new technological appliances, kitchen and cooking equipment.

Since the production sector stopped due to Covid-19, global energy needs decreased by 3.8% in the first quarter of 2020. However, the energy demand in the residential sector increased in the same period of time. [79] According to the research, energy consumption in all sectors decreased in Spain by 13.5% and in Italy by 37% during the Covid-19 lockdown in 2020 compared to 2019.[80] Although the total energy consumption has been reduced at the national level, energy use in residences has increased during the Covid-19. During the lockdown, households raised their consumption by an average of 13%.[81] The impact of lockdown on energy use changes according to month, season, and day types.

The primary energy in houses is used for heating and cooling, appliances, lighting, and cooking. Occupants are generating internal load with their presence and cause

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[77] Achraf Ammar, Patrick Mueller, Khaled Trabelsi, Hamdi Chtourou, Omar Boukhris, Liwa Masmoudi, Bassem Bouaziz, Michael Brach, Marlen Schmicker, Ellen Bentlage, et al., "Psychological Consequences of COVID-19 Home Confinement: The ECLB-COVID19 Multicenter Study," *PLOS ONE* 15, no. 11 (2020): 1–13, https://doi.org/10.1371/journal.pone.0240204.
[78] Angel M Dzhambov, Peter Lercher, Matthew H.E.M. Browning, Drozdstoy Stoyanov, et al., "Does Greenery Experienced Indoors and Outdoors Provide an Escape and Support Mental Health during the COVID-19 Quarantine?," *Environmental Research* 196, no. October 2020 (May 2021): 2, https://doi.org/10.1016/j.envres.2020.110420.
[79] Abdeen, Kharvari, O'Brien, and Gunay, "The Impact of the COVID-19 on Households' Hourly Electricity Consumption in Canada."
[80] Monzón-Chavarrías, Guillén-Lambea, García-Pérez, Montealegre-Gracia, et al., "Heating Energy Consumption and Environmental Implications Due to the Change in Daily Habits in Residential Buildings Derived from COVID-19 Crisis: The Case of Barcelona, Spain."
[81] Ibid.

great energy consumption with the use of home appliances and lighting.[82] The pattern of energy consumption in dwellings changed during the Covid-19 pandemic. The remarkable difference is that "consumption occurred throughout the day instead of being concentrated in the evening as observed before the lockdown."[83] A clear distinction between weekend and weekday profiles can be observed before the lockdown period. For the weekdays, occupants consume energy in the early morning due to working and schooling commitments, and the consumption increases during the evening since occupants return to the house. However, the day pattern is not different for weekdays and weekends in the lockdown period. The morning peak is disappeared due to remote working, and energy use gradually rises until noon. A prolonged peak can be observed during the evening due to the use of lighting.[84] The most significant result of the pandemic energy consumption studies is the similarities between pre-pandemic and post-pandemic energy use profiles during the day. Although the daily consumption amount is increases between 16.3 to 29.1%, the daily patterns are similar to each other.[85]

The energy consumption ratio in the lockdown period differs for each residence due to the differences between households. The socio-economical factors, such as age and employment status, originate the variation in energy usage. A study claims that there is "a negative correlation between the age of residents and energy consumption

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[82] Ali Cheshmehzangi, “COVID-19 and Household Energy Implications: What Are the Main Impacts on Energy Use?,” *Heliyon* 6, no. 10 (October 2020): 1–8, https://doi.org/10.1016/j.heliyon.2020.e05202.
[83] Jean Rouleau and Louis Gosselin, “Impacts of the COVID-19 Lockdown on Energy Consumption in a Canadian Social Housing Building,” *Applied Energy* 287, no. February (2021): 1–11, https://doi.org/10.1016/j.apenergy.2021.116565.
[84] Abdeen, Kharvari, O’Brien, and Gunay, “The Impact of the COVID-19 on Households’ Hourly Electricity Consumption in Canada.”
[85] Ibid.

in homes, i.e., that older residents show a more favorable pattern of behavior compared to the younger ones."[86]

Some of the consequences of the pandemic may persist for an extended period of time. Although the re-opening period is completed and the influence of the Covid-19 on daily life is minimized, the long-term effects on behavioral patterns can be observed in society. People mostly tend to spend their time in homes, socializing in open-air spaces, cooking their own foods, entertaining at home and others. As a result, the effects of the pandemic on buildings may generate renewed understanding of architecture and environmental systems to meet the new behavioral pattern. This study does not focus especially on the strict lockdown period of Covid-19; instead, it analyzes the long term effect of the Covid-19 and quantifies the impacts of lockdown on households. The aim is to investigate the changes in a household's energy consumption pattern during the post-pandemic process and represent possible future scenarios with teleworking and distance education.

With the increased environment of the new teleworking and distance education, it has become crucial to reconsider the design and operation of buildings. As functionality and technology need changes in buildings, it is critical to ensure that buildings can be inconstantly adapted to these circumstances without negatively affecting occupant well-being.[87]

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[86] Dragan Cvetković, Aleksandar Nešović, and Ivana Terzić, "Impact of People's Behavior on the Energy Sustainability of the Residential Sector in Emergency Situations Caused by COVID-19," *Energy and Buildings* 230 (January 2021): 2, https://doi.org/10.1016/j.enbuild.2020.110532.
[87] Mohamad Awada, Burcin Becerik-Gerber, Simi Hoque, Zheng O'Neill, et al., "Ten Questions Concerning Occupant Health in Buildings during Normal Operations and Extreme Events Including the COVID-19 Pandemic," *Building and Environment* 188, no. November 2020 (2021): 1–11, https://doi.org/10.1016/j.buildenv.2020.107480.

CHAPTER 3

OCCUPANCY BEHAVIORS

3.1 Definition of Occupancy Behavior

Occupants interact with the building and building control systems in order to satisfy their comfort needs by opening and closing windows, turning on/off lights, adjusting the thermostat set point, pulling up/down blinds, turning on/off AC, and moving in the building. The principles of perceived comfort, productivity, control of environmental systems, and satisfaction are the reasons behind the occupant behaviors. The interaction between occupants and building is a double-sided relation. They are the actors affected by the interior environment and also who are adjusting the control systems and change the indoor conditions. The unpredicted interaction between occupants and control systems affects the operation of buildings, thus building performance and indoor environmental quality are influenced. It is a challenging procedure to predict the occupant behavior before the building is populated, even though some estimated behaviors are considered in the early design stages. To address the rising demand for more sustainable buildings, sophisticated knowledge of the effects of occupancy on building energy performance is required. [88] However, the impact of occupant behavior and diversity is generally ignored or simplified in the design and construction stages of a building. The simplistic representation of occupants as passive and static individuals reduces

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[88] Gülsu Ulukavak Harputlugil and Merve Bedir, "Effects of Occupant Behavior on the Energy Performance of Dwellings : A Sensitivity Analysis," *Journal of Architectural and Planning Research* 33, no. 2 (2016): 159–78.

the accuracy of building performance evaluation and building operation procedures.[89]

As previously mentioned, IEA indicates occupant activities and behavior as one of the six fundamental factors that affect building energy consumption in Annex 53.[90] According to Hong and Lin, even in the same climate and the same functioning buildings' measured energy results demonstrate significant inconsistencies due to occupancy diversity.[91] The energy consumption of a building is directly related to the occupant in the space. Studies that ignore occupant behavior are difficult to achieve reliable results.[92]

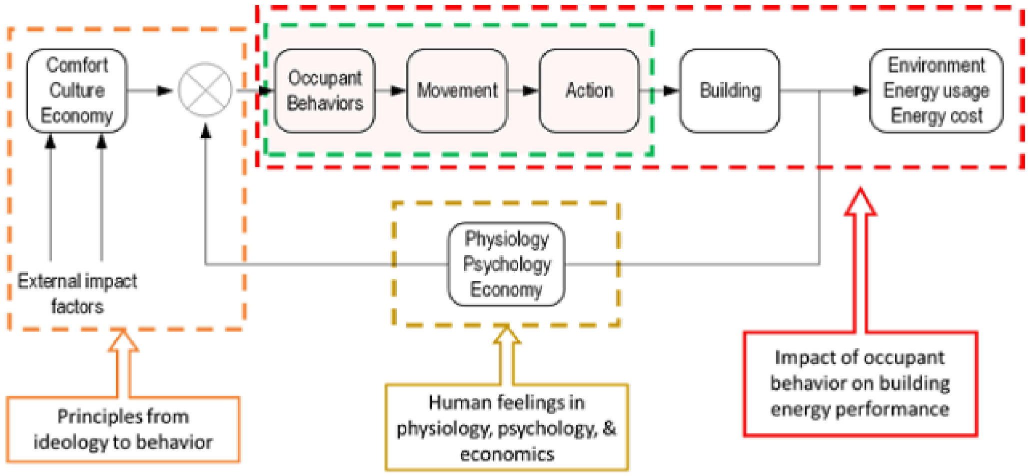

Figure 3.1 Connections of Occupancts with Builiding Systems[93]

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[89] Ardeshir Mahdavi, Farhang Tahmasebi, Burak Gunay, William O'Brien, et al., *Annex 66: Definition and Simulation of Occupant Behavior in Buildings. Technical Report : Occupant Behavior Modeling Approaches and Evaluation*, 2017.
[90] Energy in Buildings and Communities Programme (EBC), "Final Report Annex 53. Total Energy Use in Buildings Analysis and Evaluation Methods," 7.
[91] Tianzhen Hong and Hung-Wen Lin, "Occupant Behavior: Impact on Energy Use of Private Offices," *Ernest Orlando Lawrence Berkeley National Laboratory*, 2013.
[92] Gülsu Ulukavak Harputlugil and Timuçin Harputlugil, "Çevresel Konfor Ve Enerji Tasarrufu Bağlamında Konut Kullanıcıları Davranış Profilleri Üzerine Bir Araştırma," *Journal of the Faculty of Engineering and Architecture of Gazi University* 31, no. 3 (2016): 695–708, https://doi.org/10.17341/gummfd.06821.
[93] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report," 2018, 3, https://doi.org/10.15199/9.2015.5.

Figure 3.1 shows the relationship between buildings and occupants. There are external and internal factors that influence occupancy behavior. Climate, culture, and economy are examples of external impact factors. On the other hand, physiology, psychology, and personal comfort needs are the internal impact factors of occupancy. Occupant behaviors affect relations with control systems, which also influences building operations. Thus energy consumption and indoor comfort establish a closed-loop.[94]

3.1.1 Occupancy Behavior Measurements

Occupancy can be categorized into two; the first is the presence and movement in a building, and the second is the interaction between building systems, appliances, lighting, and others. Occupants' presence impacts heat and humidity production, carbon dioxide emission. However, occupant interaction influence the building performance with adaptive and non-adaptive behaviors.[95] The adaptive behaviors represent the adjustments that increase the occupant's thermal, visual and acoustic comforts. The non-adaptive behaviors are not directly related or aim to physical comfort, though they are primarily motivated by environmental factors. They are driven by the idea of saving energy, increasing their views of the outside environment, or completing a duty.[96] Table 3.2.1 clarifies and exemplifies the particular behavior measurements.

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[94] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report."
[95] Mahdavi, Tahmasebi, Gunay, O'Brien, et al., *Annex 66: Definition and Simulation of Occupant Behavior in Buildings. Technical Report : Occupant Behavior Modeling Approaches and Evaluation*.
[96] Ibid.

Table 3.1 Occupancy Model Measurements

Adaptive Behaviors	**Non-Adaptive Behaviors**	**Occupancy Model**
Occupant actions to restore occupant comfort	Occupant action driven by contextual factors	-
Light switch control	Light switch off at the departure	Presence
Appliance use	Fixed plug-in appliance use	Movement
Blind control	Blind opening at day time	Arrival / Departure pattern
Thermostat use		Presence duration
Window control		
Clothing adjustment		

The behavior of occupants also is affected by some short-term and long-term variables. The current physiological, psychological, or economic conditions of occupants can be considered as short-term variables that affect energy consumption. Long-term factors can be examplified as culture, sex, comfort, income status, age, and profession.[97]

[97] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report," 3.

3.1.2 Multidisciplinarity in the Occupancy Behavior

Occupant behavior is a multidisciplinary research topic related to social and behavioral science, building science, sensing and control technologies, computing science, and data science. Analyzing user behaviors increases the possibility of providing occupant comfort and, as a result, increases the energy efficiency in buildings.[98]

Multiple actors engage with the design, construction, operation phases of a building. Each actor has a responsibility and a role in building performance. However, the impact of these actors on building energy consumption cannot be predicted in advance. The uncertainty that occurred from the agents results in discrepancies between predicted and actual building energy performance.[99] D'Oca, Hong, and Langevin explain the effect of related disciplines as follow;

> "Building energy modelers focus on comparing design scenarios based on performance and accurately predicting building energy consumption; building occupants seek improved comfort and productivity; building operators seek to minimize daily energy use while maintaining comfort for occupants; utilities and policy makers aim to address occupants', operators', and managers' energy savings impacts through codes and standard regulations; and building vendors seek to develop high-performance products that save consumers energy costs with minimal capital investment requirements."[100]

Annex 66 was introduced by International Energy Agency (IEA) to increase the interrelationship of disciplines that have an active role in building performance. As

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[98] Hong, Taylor-Lange, D'Oca, Yan, et al., "Advances in Research and Applications of Energy-Related Occupant Behavior in Buildings."
[99] Simona D'Oca, Tianzhen Hong, and Jared Langevin, "The Human Dimensions of Energy Use in Buildings: A Review," *Renewable and Sustainable Energy Reviews* 81, no. August 2017 (2018): 731–42, https://doi.org/10.1016/j.rser.2017.08.019.
[100] Ibid., 732.

a result, further studies of occupancy and building life cycle with relevant agents decrease energy consumption while increasing indoor environmental comfort.[101]

3.1.3 Individual Effects on Occupancy Behavior

Occupancy is a complex subject and requires a multidisciplinary approach to tackle with the issue in all its aspects. Occupant behaviors have a dynamic character according to external conditions to occupants (such as wind or temperature), the internal condition of occupants (culture, age, or gender), and building properties.[102] In order to improve the energy consumption prediction of a building, researchers suggest considering sociological, psychological, and economic aspects of occupants.[103] Although individual physiological and psychological factors are studied in many research, there is a significant influence of social context on the energy consumption behaviors of occupants. Some of the social and personal parameters that affect energy consumption are socio-cultural belonging, gender, age, awareness of energy issues, employment, income, and education level.[104]

Cultural differences may result in different occupancy schedules that consequently change the energy use pattern. Shan Hu et al. has exemplified the culture effect as;

> "Every day at about 12:00 (noon) in Japan, electricity demand falls more than 6GW and then returns to the pre-lunch trend at 13:00. This phenomenon appears because the Japanese lunch hour is strongly concentrated between 12:00 and 13:00, where Japanese office workers traditionally switch off

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[101] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report."
[102] Valentina Fabi, Rune Vinther, Stefano Corgnati, and Bjarne W Olesen, "Occupants' Window Opening Behaviour : A Literature Review of Factors in Fl Uencing Occupant Behaviour and Models," *Building and Environment* 58 (2012): 188–98, https://doi.org/10.1016/j.buildenv.2012.07.009.
[103] Elham Delzendeh, Song Wu, Angela Lee, and Ying Zhou, "The Impact of Occupants' Behaviours on Building Energy Analysis: A Research Review," *Renewable and Sustainable Energy Reviews* 80, no. September 2016 (2017): 1061–71, https://doi.org/10.1016/j.rser.2017.05.264.
[104] Ibid.

> lights, equipment and sometimes even air conditioning before leaving their workspace. However, this phenomenon does not appear in major North American or European load shapes due to different office occupancy and appliance use behaviors."[105]

Different user groups not only define the energy usage pattern but also determine the consumption level. According to studies, income level is correlated with the energy use of a household. "A 1% increase in income increases the total energy consumption by 0.63%."[106] Occupants aged 40 to 50 have the highest demands for comfort and, as a result, consume more. Highly educated people have more control and knowledge of thermostat usage. The existence of a teenage person in a household affects energy use due to the increased use of appliances.[107]

There are numerous interrelating factors that affect the energy use behavior of occupants. For instance, electricity usage is correlated with income level, income level affects building physical conditions, physical condition changes the building energy consumption. Each factor correlated with the other. Interactions between human and building systems are only one feature of occupant behavior. Occupant behaviors can be explained with a combination of prementioned social features and different disciplines.[108]

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[105] Shan Hu, Da Yan, Elie Azar, and Fei Guo, "A Systematic Review of Occupant Behavior in Building Energy Policy," n.d., 7.
[106] Paula van den Brom, Arjen Meijer, and Henk Visscher, "Performance Gaps in Energy Consumption: Household Groups and Building Characteristics," *Building Research and Information* 46, no. 1 (2018): 56, https://doi.org/10.1080/09613218.2017.1312897.
[107] van den Brom, Meijer, and Visscher, "Performance Gaps in Energy Consumption: Household Groups and Building Characteristics."
[108] Fabi, Vinther, Corgnati, and Olesen, "Occupants' Window Opening Behaviour : A Literature Review of Factors in Fl Uencing Occupant Behaviour and Models."

3.2 Modeling of Occupancy Behavior

A valuable occupancy model represent collected data properly and explains comprehensive data. To determine the collection of predictor variables that form the advanced model, a model selection technique is used.[109] The modeling of occupancy behavior is the process of collecting the relevant data and generating a systematic representation with mathematical methodologies. There are various modeling approaches in the literature (such as linear models, mixed-effects models, Markov chains, and Bayesian networks) to produce different presence, movement, and action models. In IEA EBC Annex 66, five behavior models and their modeling approaches are analyzed in the occupancy studies. According to the study, window opening behavior is the most extensive model, followed by window shading arrangement, light switch use, thermostat adjustment, and appliance use models.[110]

Numerous models are produced for a large number of behaviors with greater input complexity. The complexity of the model fundamentally depends on the quality of the input variables, the size of the research environment, and the significance of the occupancy for the study. A significant number of variables need to be integrated to the occupancy model for a large scale (urban scale), correspondingly the complexity of the model increases and the reliability of the model becomes questionable.[111] The correlation between the complexity of occupancy models and model detail is inversely proportional.

Gaetani, Hoes, and Hensen groups occupancy models into five; schedules, deterministic rules, non-probabilistic models, probabilistic/stochastic models, and agent-based stochastic models. Schedules and deterministic models are available in

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[109] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report."
[110] Ibid.
[111] Isabella Gaetani, Pieter-jan Hoes, and Jan L.M. Hensen, "Occupant Behavior in Building Energy Simulation: Towards a Fit-for-Purpose Modeling Strategy," *Energy and Buildings* 121, no. March (June 2016): 188–204, https://doi.org/10.1016/j.enbuild.2016.03.038.

BPS tools and represent fundamental scenarios about building operation. The last three model types are explained by the authors;

> "As briefly stated above, three main categories are identified: non-probabilistic models, which mainly include diversity factors resulting from data-mining; probabilistic or stochastic models, which represent the majority of the considered publications and rely on Logit analysis, Probit analysis, Markov chain processes, Poisson processes, and survival analysis; agent-based and object-oriented models, also known as object-based models."[112]

Existing occupancy models in the literature are commonly based on specific studies, behaviors, and locations. The case specificity and limitation on the standardization of the models create difficulties in comparing the accuracy of the behaviors.[113]

3.2.1 Data Collection Methods

Occupant research requires a comprehensive set of occupant-related data to generate consistent occupancy models and detailed knowledge about the subject. There are various methods for data collection, and each of them has some strengths and weaknesses. The first method is the in-situ studies that observe the occupant in their daily environment with sensors. The advantages of the method are the long-term observation period and distraction-free environment. Researches that is based on the natural environment of occupants decrease the possibility of unnatural behavior of occupants. However, sensor placement and size of the study group are the

[112] Ibid., 6.
[113] Gaetani, Hoes, and Hensen, "Occupant Behavior in Building Energy Simulation: Towards a Fit-for-Purpose Modeling Strategy."

disadvantages of in-situ researches.[114] Also, privacy issues and the cost of the sensors should be considered in these studies.

The second data collection method is the laboratory studies. Occupants are observed in fully equipped environments by experts. The laboratory environments are similar to standard indoor spaces, thus the unfamiliarity of space and sense of being observed may cause unnatural behaviors. These environments are considerably costly than in-situ studies due to the quantity and variety of equipments. Nevertheless, laboratory studies create the opportunity to observe numerous aspects of occupancy behavior with the sophisticated control of indoor environmental conditions.[115]

Surveys are the last method that is constitutively based on questionnaires, interviews, and self-reporting. This method is cost-effective and may target a comprehensive group to observe that is almost impossible with in-situ and laboratory studies. The reliability of the data is questionable since limited knowledge of building systems and unclear, incorrect and garbled answers of occupants.[116] In order to obtain more accurate data, a mixed comprising method can be used by evaluating the strengths of the mentioned methods.

3.2.2 Occupancy Schedules

BPS programs often depict occupant behavior by using a variety of techniques that include simplistic or predefined static schedules, as well as predefined settings. These schedules are not affected by design and individual differences since the

[114] Energy in Buildings and Communities Programme (EBC), "Annex 66: Definition and Simulation of Occupant Behavior in Buildings. Technical Report: Studying Occupant Behavior in Buildings: Method and Challenges," 2017.
[115] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report."
[116] Ibid.

occupants are perceived as passive recipients.[117] Static schedules that are the early examples of occupancy schedules represent an unrealistic result of energy use compared to real life and ignore individual differences and stochastic energy-related behaviors of occupants. Deterministic rules can be assigned to the occupancy schedules in order to increase the model resolution and the complexity. The deterministic rules are applicable "where actions are perceived as direct consequences of one or more drivers e.g., variation of indoor temperature or direct solar radiation."[118] The non-probabilistic models are produced based on a specific data set and are considered to include information about environmental triggers.

The sophisticated and dynamic nature of occupant behaviors leads to studies focusing on agent-based and stochastic representation. Actions occur in stochastic models based on a probability function as a result of inputs. The behavior is often predicted according to the Markov chain model that is based on the likelihood of occurring an action in the following time step independently from current conditions.[119] The accuracy increases by the multiple simulation processes. Although some stochastic models are included in performance simulation programs, the tools allow defining user-defined schedules independently.[120]

"Schedules, deterministic, non-probabilistic, and probabilistic models represent the conventional simulation framework"[121] compared to agent-based occupancy models. Individuals are represented as autonomous agents with personal attributes in agent-

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[117] Yoon Soo Lee and Ali M. Malkawi, "Simulating Multiple Occupant Behaviors in Buildings: An Agent-Based Modeling Approach," *Energy and Buildings* 69 (2014): 407–16, https://doi.org/10.1016/j.enbuild.2013.11.020.
[118] Gaetani, Hoes, and Hensen, "Occupant Behavior in Building Energy Simulation: Towards a Fit-for-Purpose Modeling Strategy," 4.
[119] Mahdavi, Tahmasebi, Gunay, O'Brien, et al., *Annex 66: Definition and Simulation of Occupant Behavior in Buildings. Technical Report : Occupant Behavior Modeling Approaches and Evaluation*.
[120] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report."
[121] Gaetani, Hoes, and Hensen, "Occupant Behavior in Building Energy Simulation: Towards a Fit-for-Purpose Modeling Strategy," 5.

based occupancy schedules, and their individual variability is considered. Agent-based schedules introduce the social interactions between agents and their surrounding environment. The distribution of stochastic predictions of occupancy levels is similar to the actual occupancy level.[122]

Building performance simulations commonly operate static schedules due to their present and easy access in the simulation programs. However, agent-based occupancy schedules represent each occupant as an independent entity with stochastic behaviors. Therefore, agent-based schedules enhance the accuracy and reliability of the predicted energy use results.

3.3 Simulation of Occupant Behavior

The influence of occupant behavior on building energy consumption is a well-known fact. Integration of occupancy models with the building performance simulation is a must to be able to evaluate the occupancy effect on energy use. In a building performance simulation, occupancy schedules imitate real-world occupant behaviors, taking into consideration the behavior's effect on thermal aspects and energy consumption in the building.[123]

There are fundamentally four reasons for occupancy simulations. The most prevalent aim is the estimate building energy consumption to determine the control systems of the building. Predicting occupant behavior before the building is occupied is the second purpose of the simulations. Also, the other aims of the occupancy simulations are adjusting building systems depending on human building interaction and

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[122] Farhang Tahmasebi and Ardeshir Mahdavi, "The Sensitivity of Building Performance Simulation Results to the Choice of Occupants' Presence Models: A Case Study," *Journal of Building Performance Simulation* 10, no. 5–6 (2017): 625–35, https://doi.org/10.1080/19401493.2015.1117528.

[123] Chen, Liang, Hong, and Luo, "Simulation and Visualization of Energy-Related Occupant Behavior in Office Buildings."

evaluating occupancy models based on obtained data.[124] The more realistic influence of the occupancy on building energy use is obtained by the stochastic behaviors simulations rather than fixed occupancy schedules in BPS programs. However, implemanting occupancy scheudules to BPS programs require a deep knowledge and expertise about the subject.

There are some key variables that affect the simulation of occupancy behaviors. These variables are similar to real-life trigger factors that start or end an comfort related action. For instance, entering or leaving a room is a time-related parameter for occupancy behavior. Indoor air quality and outdoor temperature can be used as a parameter for window opening/closing action. An advanced observation of real-world data is required to identify trigger variables that may cause actions.[125]

3.3.1 Building Performance Simulation Tools and Occupancy Behavior Modeling

According to 95 studies on the occupancy researches in the last 15 years, EnergyPlus (43%) is the most common program to represent building performance and human building interaction as followed by MATLAB (16%), ESP-r, Modelica, Python, TRNSYS, eQuest, AnyLogic, C++, and DeST. In addition to reviewed articles in the study, other modeling and simulation tools are also commonly available such as DOE-2, WUFI, and IDA.[126] The main purposes of the tools are generating a standardization of occupant behavior models, improving the reliability and consistency of the simulations by integrating occupancy scheduled with BPS, and creating realistic occupancy behavior models. In order to achieve advanced

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[124] Norouziasl, Jafari, and Zhu, "Modeling and Simulation of Energy-Related Human-Building Interaction : A Systematic Review."
[125] Ouf, O'Brien, and Gunay, "Improving Occupant-Related Features in Building Performance Simulation Tools."
[126] Norouziasl, Jafari, and Zhu, "Modeling and Simulation of Energy-Related Human-Building Interaction : A Systematic Review."

simulations, these tools represent the complexity, diversity, and stochasticity of occupant behavior in buildings.[127]

BPS programs represent occupants as internal heat gain sources similar to appliances. Although thermal load accuracy is increased, the action and movement of the occupant is ignored in the default schedules. User-defined occupancy schedules can be integrated into BPS to define stochastic features to the schedules. Researchers have developed particular mathematical functions to update default schedules.[128] The user-defined schedules create great flexibility to define specific rules and schedules for energy simulations.

There are 52 occupancy behavior models publicly available in the Lawrence Berkeley National Laboratory (LBNL) website. These models are produced based on real occupancy data and window, blind, light, heating, and AC operations are modeled as user-defined schedules.[129] The following chapter describes the methodology and working principles of these occupancy behavior schedules.

3.3.2 Integration of Occupancy Behavior Models with Building Performance Simulations

Many of the BPS programs contain occupancy, equipment, and lighting schedules that are generally fixed schedules. Energy Plus (EP) is a performance simulation tool, and a more user-friendly interface for EP is obtained with the Honeybee, an application in the Grasshopper. The existing schedules in the EP represent constant values for each week. The schedules can be regenerated by defining some

[127] Energy in Buildings and Communities Programme (EBC), “Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report.”
[128] Ouf, O’Brien, and Gunay, “Improving Occupant-Related Features in Building Performance Simulation Tools.”
[129] Zsofia Belafi, Tianzhen Hong, Andras Reith, and Building Performance Simulation, “A Library of Building Occupant Behaviour Models Represented in a Standardised Schema,” in *4th European Conference on Behaviour and Energy Efficiency*, 2016.

deterministic rules. For instance, natural ventilation patterns can be defined in BPS tools with the reference parameter to the indoor air temperature or indoor CO2 concentration. The non-deterministic models can be integrated with the BPS programs by using CSV files that are generated by the real data.

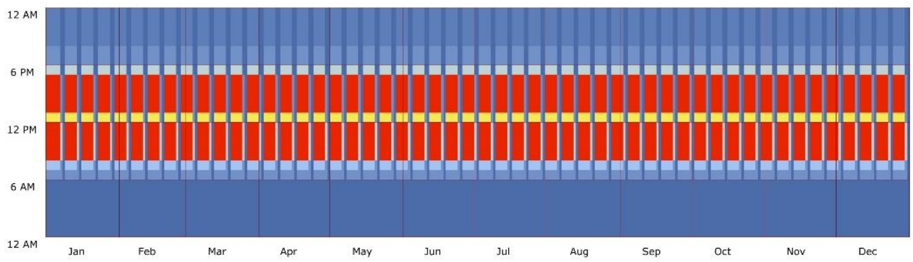

Figure 3.2 Existing Occupancy Schedule in Energy Plus

Stochastic and agent-based models require advanced knowledge of the BPS tools for integrating with the simulation programs. Since there is a great need for standardization of occupancy behavior models, researchers have developed obXML (occupancy behavior eXtensible Markup Language) based on the DNAS (Drivers, Needs, Actions, Systems) framework.[130] DNAS framework explained in IEA EBC Annex 66 as;

> "Drivers represent the environmental and other context factors that stimulate occupants to fulfill a physical, physiological, or psychological need. Needs represent the physical and non-physical requirements of occupants that must be met to ensure satisfaction with their environment. Actions are the interactions with systems or activities that occupants can perform to achieve environmental comfort. Systems refer to the equipment or mechanisms

[130] Tianzhen Hong, Yixing Chen, Zsofia Belafi, and Simona D'Oca, "Occupant Behavior Models: A Critical Review of Implementation and Representation Approaches in Building Performance Simulation Programs," *Building Simulation* 11, no. 1 (February 27, 2018): 1–14, https://doi.org/10.1007/s12273-017-0396-6.

within the building that occupants may interact with to restore or maintain environmental comfort." [131]

The window opening action based on interior temperature is explained in DNAS format as; Driver is the indoor temperature, Need is the thermal comfort, Action is open and System is the window.

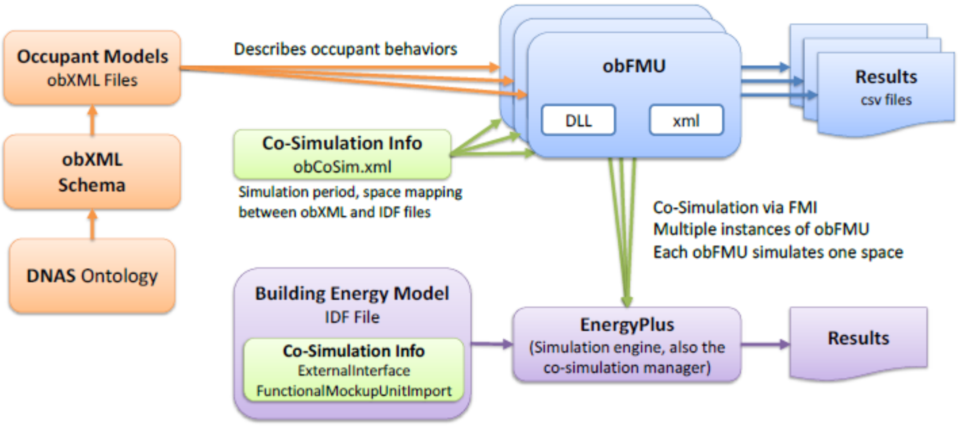

Figure 1 Data flow of co-simulation between EnergyPlus and obFMU

Figure 3.3 Data Transmission Between obXML, obFMU and Energy Plus[132]

Occupant models in obXML format are co-simulated with the obFMU (occupancy behavior Functional Mockup Unit) to integrate into BPS programs. The obXML defines the variables for the obFMU and obFMU simulate the occupancy behavior according to XML file and drivers.[133] Figure 3.3 explains the data flow between obXML, obFMU, and Energy Plus.

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[131] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report," 73.
[132] Belafi, Hong, Reith, and Simulation, "A Library of Building Occupant Behaviour Models Represented in a Standardised Schema."
[133] Ibid.

3.3.3 Limitations of Simulated Models

Numerous methodologies and models are produced to understand and decrease the gap between simulated and actual building energy use by expressing occupant behavior in building performance simulations. IEA EBC Annex 66 collects the occupancy related researches under a study to guide the calculation of predicted occupancy and internal heat gains of a design instead of the rule-of-thumb of design standards.[134] However, architects are not fully advanced yet with occupant behaviors' environmental and comfort implications.

Since the influence of occupancy on energy consumption varies according to design schema, interior organization, the relation between internal and external thermal loads, degree of automation, the choice of occupancy models should correspond to building context and features. "Increasing modeling complexity of non-influential occupancy behavior aspects does not lead to improved results, but involves an unnecessary time expenditure."[135] Detailed models with various inputs may result in more accurate simulations; nevertheless, determining the degree of details according to the intended use of the model provides more efficient results. The best way to select the convenient occupancy model is considering the "who," "what," "why," "when," and "where" questions for each particular case.[136] Accordingly, stochastic models do not always exhibit preferable data to deterministic models.

The occupancy models produced according to real data generally depend on a limited observation group and specific building type. The availability of limited occupancy data is unreliable due to the lack of demographic variety and condensed data collection durations. Therefore, the studies often question the transferability of the

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[134] Energy in Buildings and Communities Programme (EBC), "Annex 66 Definition and Simulation of Occupant Behavior in Buildings Final Report," 104.
[135] Ibid., 103.
[136] Ibid.

behavior models based on observation.[137] These occupancy models are not considered validated according to a limited set of data and can not be applied to all building types, locations, and populations. Another limitation of real data is the behavioral change of occupants due to being aware of the observation process.

The limited number of BPS programs support integrating occupancy schedules into their layout. This process requires advanced knowledge about the BPS tools. "The simulation platforms that permit the incorporation of custom component models (e.g. occupant models) in BPS tools are not mature enough to provide a standardized and user-friendly interface for the rapid implementation."[138] For this reason, the widespread use of energy simulations in design processes is limited.

[137] H. Burak Gunay, William O'Brien, and Ian Beausoleil-Morrison, "Implementation and Comparison of Existing Occupant Behaviour Models in EnergyPlus," *Journal of Building Performance Simulation* 9, no. 6 (2015): 567–88, https://doi.org/10.1080/19401493.2015.1102969.
[138] Ibid., 568.

CHAPTER 4

THE CASE STUDIES

4.1 Household Typologies in Turkey

Turkish Statistical Institute (TUIK) compiles, evaluates, analyzes, and publishes the statistics of the country in the fields of economy, social issues, demography, culture, environment, science and technology, and other fields deemed necessary.[139] TUIK conducted a study on the average household size in 2020. According to the research, the current average household is composed of 3.30 occupants.[140]

Table 4.1 Number of Households by Size and Type, 2020

Type of household	**Number of households**	**1**	**2**	**3**	**4**	**5**	**6+**
One-person households	4 404 997	100	-	-	-	-	-
One-family households	16 050 444	-	29.3	26.6	26.3	11.7	6.2
Couple without children	3 327 655	-	100	-	-	-	-
Couple with children	10 341 665	-	-	34.6	38.6	17.5	9.3
Lone parents with child	2 381 124	-	57.9	28.6	9.4	2.7	1.4
Extended-family household	3 456 651	-	-	13.3	18.9	21.9	46
Multi-person no-family households	691 994	-	69.6	14.6	6.1	3.8	6
Total	**24 604 086**	**17.9**	**21.1**	**19.6**	**20**	**10.8**	**10.6**

139 *Duties and Authorities*. TÜİK. (n.d.). Retrieved January 28, 2022, from https://www.tuik.gov.tr/Kurumsal/Gorev_Yetkileri

140 TUIK, "İstatistiklerle Aile," no. 37251 (2020): 5–10, https://data.tuik.gov.tr/Bulten/Index?p=Istatistiklerle-Aile-2020-37251.

According to the data, one-family with two people create the majority of all household types with the 4 705 301 households. Predominantly, 71% of this typology is composed of the couple without children, and the rest 29% is the lone parent with the child. This one-family household type is followed by the residents with one and two children owned families. One-person households have increased in 2020 and constituted a majority of 18% among all typologies. A defined dominant group of extended-family residences is composed of 6 and more households and has a rate of 46% in this type. Lastly, multi-person no-family households represent the shared house typologies and commonly, the residence contains two households that do not belong to the family.

The thesis analyzes the TUIK household data in order to generate the case study occupancies. Thus, the study involves the common household types and corresponds to the real data in Turkey.

4.2 Research Method

The case studies were conducted in five stages. Firstly, four household typologies were selected by TUIK household data in order to cover the majority of the society in Turkey. Second, the energy-related daily routines of a household were obtained by a focus group study composed of selected typologies. Occupancy, appliances, and lighting schedules were generated by the result of the focus group study in the third stage. After that, building performance simulations were performed in Honeybee and Energy Plus, with the schedules based on the daily patterns of occupants. And finally, the results of the simulations were analyzed and investigated with the existing literature studies to evaluate the accuracy of the study.

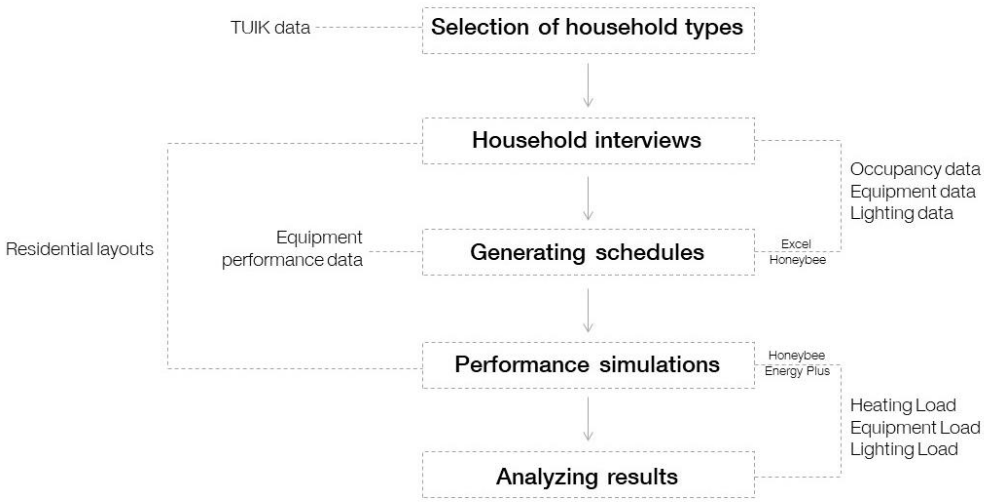

Figure 4.1 Methodology of Research

The focus group is composed of the prementioned four selected household typologies: one person, couple without a child, couple with two children, and an extended family with six members. All residences are located in Ankara, Çankaya region. The interview was conducted in a focus group of one member from each household on November 2021. In the first phase of the interview, all household members' demographic information (e.g., age, gender, education level, income level, employment status) was collected. All adults in the study are at least have a bachelor's degree and currently belong to the working class, and the income level is relatively high. Children and teenagers continue their education, and elderly people are retired.

In the second phase, architectural information about residences was requested. Members of one person, a couple with two children, and extended family households shared plan layouts and size information by the websites of the residences. And the information of the only couple's residence was collected by the author. Height information of each residence is expected as the same and 2.70m. According to the information collected, all houses are modeled in Rhino by the author.

In the following stage, possible household appliances and lightings were listed (in chapter 4.3), and the focus group determined the existing and used equipments from the list. Since the study aims to make a comparative analysis, the model and energy consumption differences are ignored for each type of appliance in itself and excepted with an average energy use data in Table 4.3 for the simulations.[141]

The final objective of the interviews was the depiction of 24-hour daily life in the house on both weekdays and weekends. The significant information of the daily routines is the presence of occupants in the dwelling, lighting preferences, and how long the occupants used which equipment. The leading questions are; “Is the occupant presence in the house?”, “If they present, in which room the occupant is?” and “What is he/she doing in that room?” In this stage, the focus group determined the usage times for each appliance. The usage time of the equipment that is not used every day was equally distributed over the days. For instance, if a washing machine is used only on Saturday for two hours, the schedules represent this information as one-hour usage for each weekend day.

The study is purely focusing on occupancy and occupant behavior. Since the individual features are correlated with each other, the focus group consisted of people with similar demographic features.

4.3 Developing an Exploratory Analysis to the Residential Energy Consumption

Since the occupant and their behavior are major components of energy consumption in the built environment, research on the interaction between the occupant and the building is significant for generating new areas of architectural inquiry.[142] Analyzing occupant characteristics is a productive technique to investigate the impact of inhabitants on residential energy usage. Energy-related knowledge on household

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[141] Energy Consumption Information Retrieved January 23,2022 from https://www.samsung.com/tr , https://www.siemens-home.bsh-group.com/tr/ and, https://www.philips.com.tr/
[142] Ebru Ergöz Karahan, Özgür Göçer, Kenan Göçer, and Didem Boyacıo, “An Investigation of Occupant Energy-Saving Behavior in Vernacular Houses of Behramkale (Assos),” 2021, 1–23.

types helps to enhance general information on the overall consumption in the residential sector.[143]

Former studies on the energy usage of the built environment have claimed that the major variable for the performance gap is occupancy. Although this is not completely irrelevant, most of the current studies have established the existence of many influential factors, such as building characteristics, together with occupancy.[144]

Heating, appliances, water heating, cooking, and lighting are the main sources of energy consumption in a residential building.[145] The heating energy need mainly depends on the building characteristics rather than the occupancy effect. However, the users and the household profile highly affect appliances and lighting. This study investigates the impact of different households and resident types on the building energy consumption in terms of heating load, equipment load, and lighting load during the post-pandemic lifestyle.

Four types of households in different sizes of houses were simulated and analyzed in order to understand the effect of the size of the house and the number of occupants in the residential buildings. Houses are mainly composed of living room (LR), kitchen (K), bedrooms (BD), bathrooms (BA), corridor (C), and laundry (L). Multiple user types are considered according to the post-pandemic work and education conditions.

According to the existing schedules in BPS tools, residential buildings are occupied between 5 pm to 8 am. However, this is not the case in real life regardless of Covid-19. Many possibilities disprove the existing occupancy schedules, such as the

143 van den Brom, Meijer, and Visscher, "Performance Gaps in Energy Consumption: Household Groups and Building Characteristics."
144 Kirsten Gram-hanssen, "Efficient Technologies or User Behaviour , Which Is the More Important When Reducing Households' Energy Consumption ?," 2013, 447–57, https://doi.org/10.1007/s12053-012-9184-4.
145 van den Brom, Meijer, and Visscher, "Performance Gaps in Energy Consumption: Household Groups and Building Characteristics."

existence of nonworker individuals, elderly persons, or under school-age children. The schedules for the presence of occupancy, equipment usage, and lighting were produced particularly for each room in each case by the author according to the focus group study. Energy Plus and Honeybee were used to integrate schedules and simulate the building performance. Since the Honeybee does not include room separation for residential buildings, the loads for each room were separately defined according to the existing occupancy, appliances, and lighting loads.

The author has interviewed the focus group composed of members of the dominant household typologies according to the TUIK, which are single person, couple without a child, couple with two children, and extended family with two elderly and couple with two children households. The selected focus group is composed of working people and their children. The schedules and plan layouts were produced based on the information gathered from the study. Weekly schedules were produced with the different behaviors for weekdays and weekends. In some cases, multiple weekday schedules are used to define the occupant behavior during the week.

Table 4.2 Household Types in the Case Study

	Household 1	Household 2	Household 3	Household 4
Total Area of House	44.5	74.25	100	149.25
Number of Rooms	1LR – 1K – 1BR – 1BA – 1C	1LR – 1K – 2BR – 1BA-1C	1LR – 1K – 3BR – 2BA - 1L-1C	1LR – 1K – 4BR – 2BA - 1C
Number of Occupant	1	2	4	6

Since the energy efficiency of the electrical appliances in the houses is increased, the energy consumption of these appliances and lighting were calculated based on the efficiency standards of the technical product data. The facade direction of the cases is accepted as the north and east in order to prevent different heating energy and lighting needs caused by the direction differences. All cases are naturally ventilated, and windows are open when the dry bulb temperature is higher than 22°C. The heating setpoint is fixed to 21°C both in day and night. Heating energy source is chosen as electricity to make a comparative analysis between heating, equipment, and lighting loads.

Table 4.3 Appliance and Lighting Energy Consumption Data[146]

Appliance	Watt (W)	Usage in a Hour (h)	Watt x Time (Wh)
Refrigerator	38	1 h	38
Dishwasher	300	1h	300
Oven	2000	1h	2000
Microwave	800	0.2h	160
Coffee Machine	1000	0.5h	500
Toaster	2000	0.2h	400
TV	98	1 h	98
Washing Machine	223	1 h	223
Dryer	1000	1 h	1000
Iron	2400	1 h	2400
Hair Dryer	1600	0.1 h	160
Vacuum Cleaner	1000	1 h	1000
Laptop	90	1 h	90
Printer	15	0.1 h	1.5
Phone Charger	4	1 h	4
LED Blub	12	1 h	12

[146] Energy Consumption Information Retrieved January 23,2022 from https://www.samsung.com/tr , https://www.siemens-home.bsh-group.com/tr/ and, https://www.philips.com.tr/

4.4 Production of Schedules

There are two main goals for the case studies; one is observing the effect of different schedules on building energy consumption studies. The other is to compare the various households' energy consumption for heating, equipment, and lighting needs. The case studies are adopted to the research to analyze the energy performance simulation results of different residential buildings and occupancy schedules. This chapter explains the production processes of the occupancy, appliance, and lighting schedules in each case for energy simulation in Honeybee with Energy Plus.

4.4.1 Occupancy Schedules

Occupancy presence schedule was defined for every room that is occupied at least an hour during a day. Firstly, the maximum capacity of each room was determined with reference to the focus group interview. The program requested the occupancy load as the number of people per area (ppl/m^2); therefore, the occupancy load for each room is unique. Lastly, the presence of the inhabitant was specified with the daily schedules. Since the Honeybee is requested the schedule values between 0 and 1, the occupancy schedule was designated with the ratio of the existing occupant to the maximum capacity. For an annual simulation, weekdays and weekends were estimated, and the pattern is accepted as the same during the year.

4.4.2 Equipment Schedules

The working principles of the appliance schedule show resemblance to the occupancy schedule in terms of load calculation and schedule determination. According to the existing type of appliances, the total energy load was calculated in reference to Table 4.3 for every room with appliances. The equipment load was defined as the load per area (W/m^2) for Honeybee. The schedule was assigned according to the ratio of active appliances to the total load of the room. A weekly schedule was used for annual simulation.

4.4.3 Lighting Schedules

The interviewees stated the type and number of lighting fixtures. In reference to this information, lighting density per area (W/m^2) was calculated and defined to the Honeybee. Since the lighting need differs during the year, it has been accepted that the optimum need for artificial lighting occurs after 6 pm. The schedule was designated similar to the previous schedules with the ratio of active lighting to the total capacity of the room. Weekdays and weekends were calculated for a yearly simulation, and the pattern is assumed to be consistent throughout the year. Daylighting conditions were not considered in the study. All windows height in the residences are accepted as the same and 150 cm.

4.5 Household Type I

Single-person households constitute 18% of all household typologies in Turkey. In the first case, a single-person household is represented in a 44.5 m^2 residence. The occupant is an employee and works from home for three days, and compulsory to commute to work for two days a week. The energy usage for the commute to work is not calculated in daily consumption. The weekend is not occupied with any obligatory activity.

The cooling energy need of the building is ignored, and windows are accepted as open when the dry bulb temperature exceeds 22°C. The heating setpoint is set to 21°C.

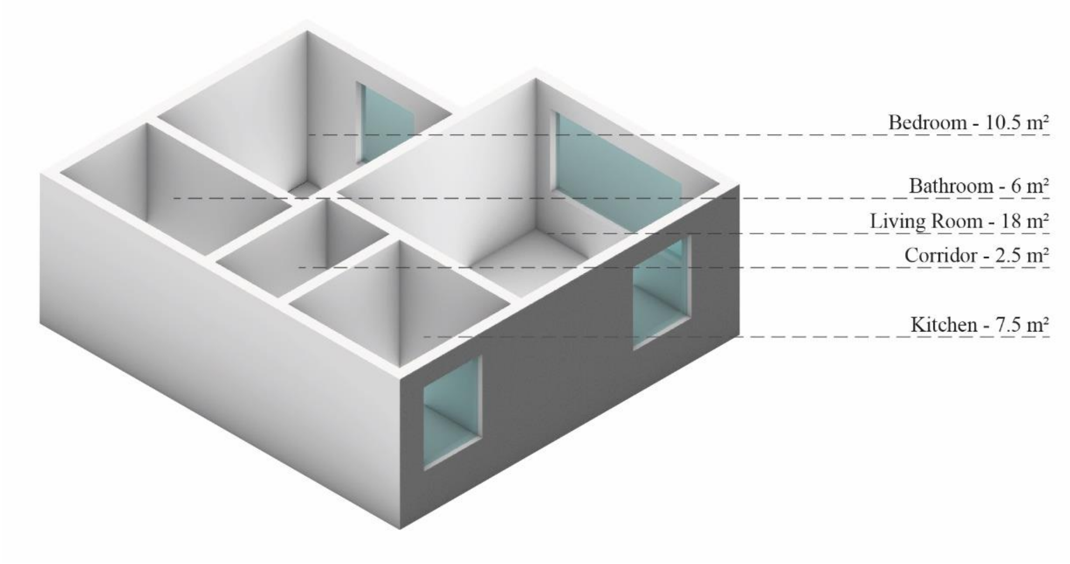


Figure 4.2 Isometric Plan Layout Representation of Case Study-I

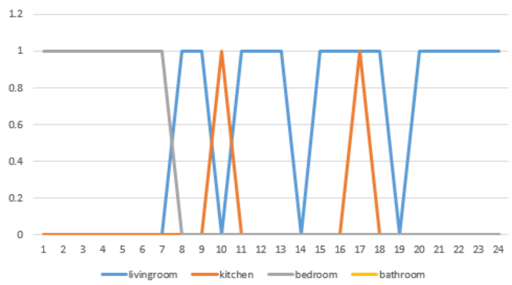
The residential building is located in Ankara, Turkey, 5A climate zone according to ASHRAE standards. Materials are also defined as standard according to ASHRAE. The residence is an apartment house composed of five spaces; a living room, a bedroom, a kitchen, a bathroom, and a corridor. The penetration on the facades is located in the north and east directions.

Table 4.4 General Energy Consumption of Household I

	Area (m^2)	Total Energy (kWh)	Energy per Area (kWh/m^2)	Heating Energy (kWh)	Appliance Energy (kWh)	Lighting Energy (kWh)
Household I	44.5	4842.4	108.8	2738.5	2041.9	62

4.5.1 Occupancy Schedule

Since the house is occupied only by a single user, the maximum number of occupants in each space is equal. As previously mentioned, the occupant works three days as teleworking and two days as regular. The house is unoccupied between 8 am and 6 pm on office workdays. The usage of the spaces changes according to the teleworking days, office workdays, and weekends. The presence of the occupant affects the energy need for heating and the usage of equipment and lighting. As a result, appliance and lighting schedules show similarities with the occupancy schedules. Since inhabitat is a source of internal heat gain and the heating setpoint is constant, the heating energy consumption decreases when the building is occupied.



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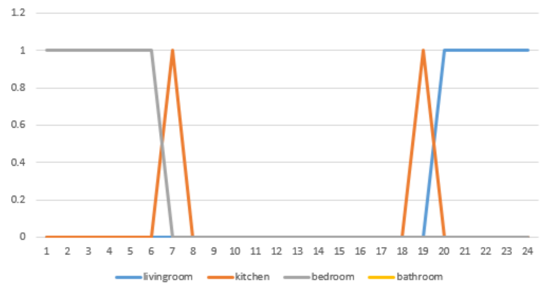

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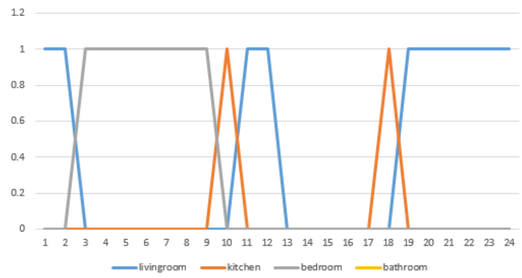


(c)

Figure 4.3 Weekly Occupancy Schedule of Household I: (a) teleworking days, (b) office workdays, (c) weekends

4.5.2 Equipment Schedule

The appliance for each room is determined based on the interview with the occupant. The kitchen has the highest equipment load per area since the existence of multiple types of appliances. The high load in the living room is caused by the use of iron in the room. Similarly, the use of vacuum cleaner in the bedroom is increasing the appliance load of the space. The corridor is not used for any appliances, therefore not represented in the graphs.

Table 4.5 Equipment List and Load in Each Room for Household I

LR	K	BR	BA
TV	Refrigerator	Vacuum Cleaner	Washing Machine
Laptop	Dishwasher	Phone Charger	Hair Dryer
Phone Charger	Oven		
Iron	Coffee Machine		
	Microwave		
144 W/ m²	**285.52 W/ m²**	**133.87 W/ m²**	**63.83 W/ m²**

The maximum consumption occurs on the weekend days, and the minimum belongs to office workdays. The peak hour in the three conditions is different for the three cases. The kitchen is the most energy-consuming room in the house.

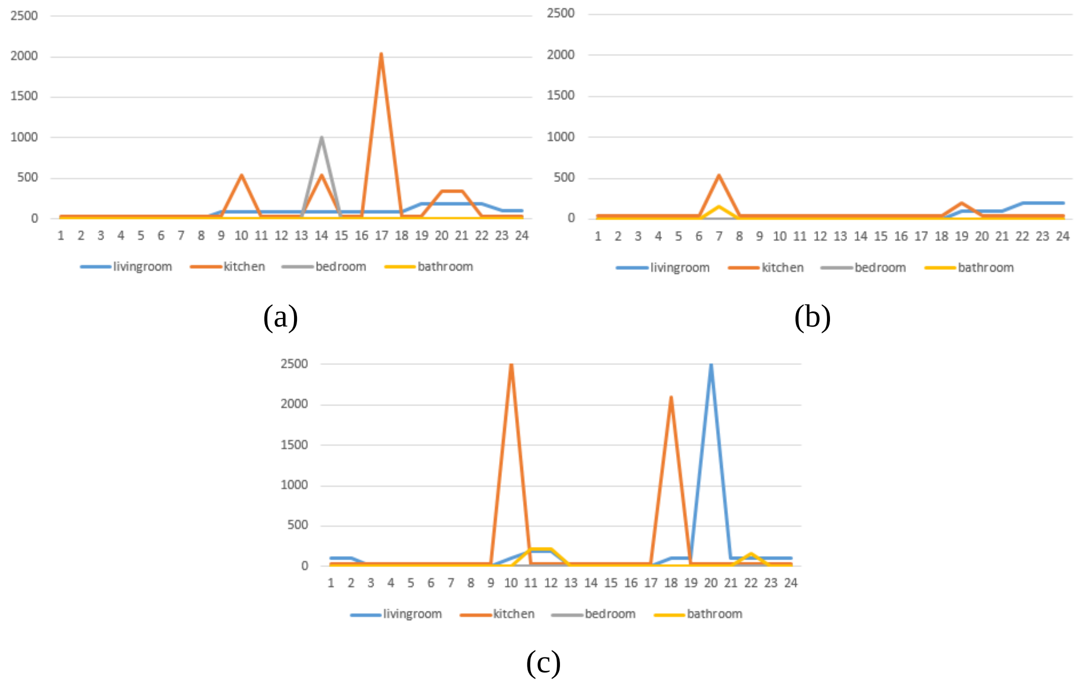


Figure 4.4 Weekly Equipment Schedule of Household I: (a) home office days, (b) office workdays, (c) weekends

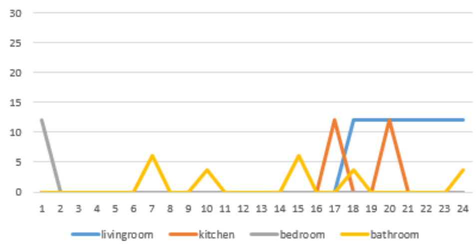
4.5.3 Lighting Schedule

Lighting energy consumption is not significantly affected by the post-pandemic condition. The existing number of lighting fixtures is determined by the occupant. The user does not specify the type of lighting, and LED bulb (12 W) is accepted for each specified existing fixture.

Table 4.6 Lighting Load in Each Room for Household I

LR	K	BR	BA
24 W	12 W	24 W	24 W
1.33 W/ m²	**1.14 W/ m²**	**3.20 W/ m²**	**4 W/ m²**

Since the consumption is determined based on the nighttime, the distinctive critical factor is the existence of occupant in the house during the nighttime. Also, the activity changes the need for lighting. For instance, the occupant has indicated reducing the amount of lighting while using the TV. The bathroom is the only room that needs lighting during the daytime.



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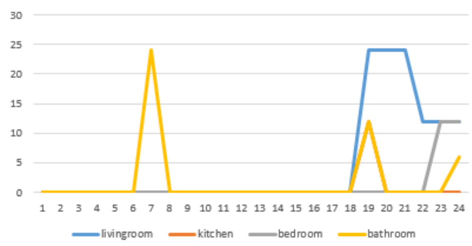


(b)

(c)

Figure 4.5 Weekly Lighting Schedule of Household I: (a) home office days, (b) office workdays, (c) weekends

4.6 Household Type II

The most dominant household typology is composed of two people and generates 21% of all households. More than 90% of this type is constituted by families without any children. In household II, a couple was investigated in an 86.5 m2 apartment house for the case study. Both occupants are employee and work from home on weekdays during the Covid-19 pandemic. There are no mandatory activities scheduled for the weekend.

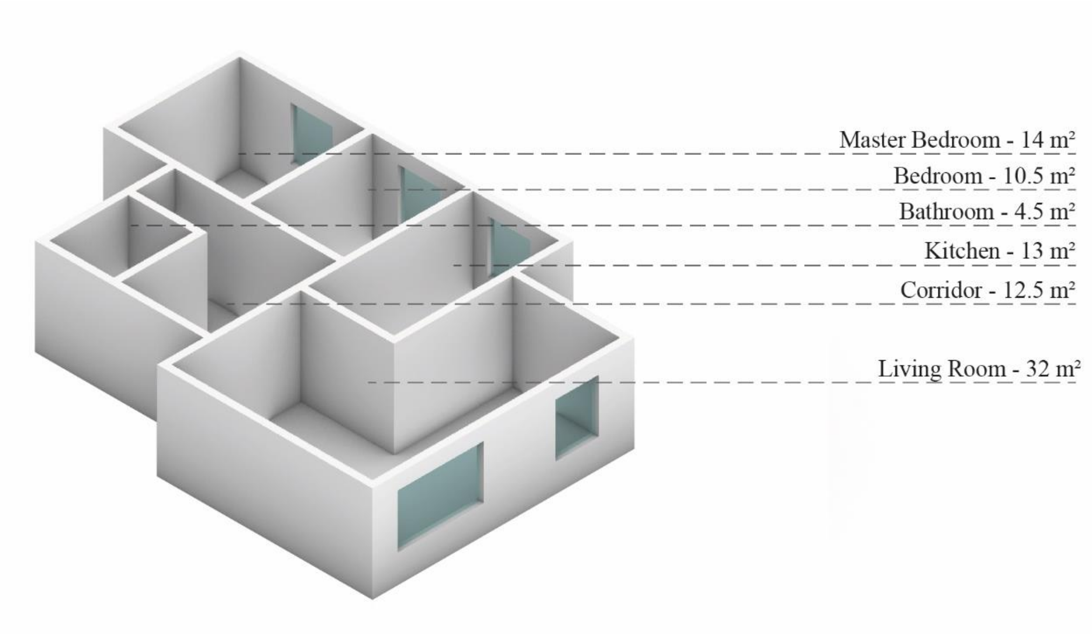


Figure 4.6 Isometric Plan Layout Representation of Case Study-II

The residential building is located in Ankara, Turkey, according to ASHRAE standards 5A climate zone. The apartment consists of a living room, two bedrooms, a kitchen, a bathroom, and a corridor. One of the bedrooms is used as an office room. In order to ignore the differences that may occur due to the facade direction, the house has windows on the north and east facades.

When the dry bulb temperature surpasses 22°C, windows are considered as open, and the apartment is naturally ventilated. The building's cooling energy need is ignored.

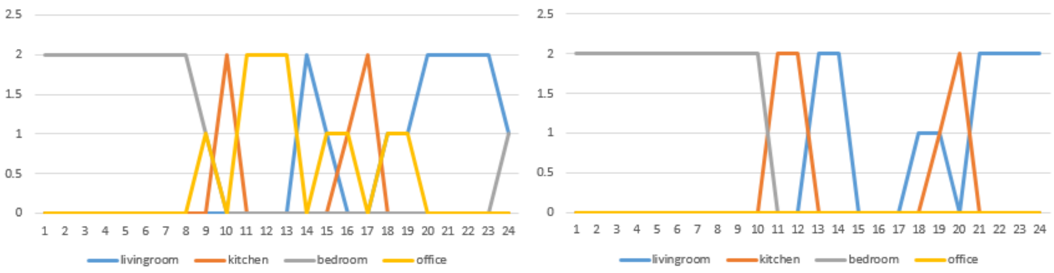
Table 4.7 General Energy Consumption of Household II

	Area (m^2)	Total Energy (kWh)	Energy per Area (kWh/m^2)	Heating Energy (kWh)	Appliance Energy (kWh)	Lighting Energy (kWh)
Household II	86.5	6252.2	72	3855.1	2332.4	64.6

4.6.1 Occupancy Schedule

The occupant load for each room is calculated with the ratio of the occupant to the area of the room as ppl/ m^2. According to the focus group interview, since both occupants are teleworking, each room is occupied with a maximum of two people during the week. The house is fully occupied on weekdays, and occupants leave the house for two hours during weekends. The movement in residence is more active on weekdays since the day started earlier, and the use of the room is diverse.

The presence of an occupant influences the amount of energy required for heating as well as the use of equipment and lights. As a result, other schedules resemble the occupancy schedules.



(a) (b)

Figure 4.7 Weekly Occupancy Schedule of Household II: (a) weekdays, (b) weekends

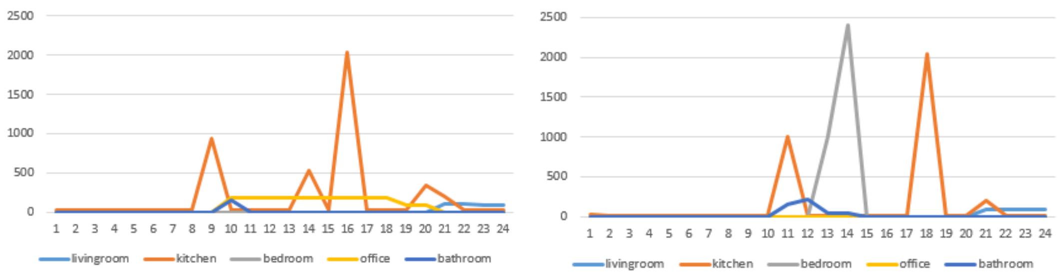
4.6.2 Equipment Schedule

The occupants have provided the equipment information in the rooms. The energy consumption of the appliances is calculated based on the information in Table 4.3. The kitchen has the largest equipment load per space because of the variety of appliances. The excessive load in the bedroom is derived from high energy-consuming appliances that are vacuum cleaner and iron. Although the excessive consumption of these appliances, their usage time is relatively limited according to the others. As a result, the influence of high consuming equipments on instant energy use can be observed as excessive; however, total energy usage is affected relatively less. There are no appliances used in the corridor.

Table 4.8 Equipment List and Load in Each Room for Household II

LR	K	BR	BR 2	BA
TV	Refrigerator	Vacuum Cleaner	Laptop	Washing Machine
Phone Charger	Dishwasher	Iron	Laptop	Hair Dryer
	Oven		Printer	
	Coffee Machine		Phone Charger	
	Toaster			
3.21 W/ m²	**249.08 W/ m²**	**242.86 W/ m²**	**18.70 W/ m²**	**79.79 W/ m²**

The peak consumption time on weekdays and weekends is different from each other. The maximum consumption is represented around 4 pm on weekdays for the preparation of the early dinner. However, the energy use increases around 1 and 2 pm on the weekend due to the use of high-consuming appliances.



(a) (b)

Figure 4.8 Weekly Equipment Schedule of Household II: (a) weekdays, (b) weekends

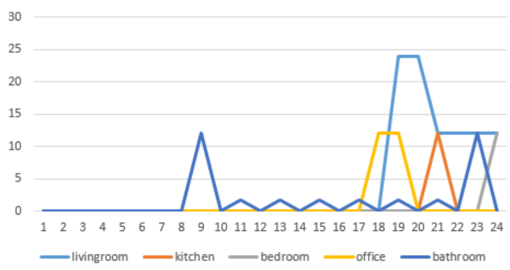
4.6.3 Lighting Schedule

The introduction of new lighting technologies, as well as modifications in lighting efficiency, have resulted in significant decreases in the proportion of energy consumption. The amount of energy consumed for lighting is considerably less than for heating and household appliances. According to the determined lighting number, the energy consumption is calculated according to the LED bulb (12 W) in Table 4.3.

Table 4.9 Lighting Load in Each Room for Household II

LR	K	BR	BR 2	BA
24 W	12 W	12 W	12 W	12 W
0.76 W/ m²	**0.92 W/ m²**	**0.86 W/ m²**	**1.13 W/ m²**	**2.50 W/ m²**

The lighting usage naturally concentrated in night time except for the use in the bathroom. Because consumption is determined at night, the critical distinguishing feature is the presence of occupants in residence during the night. The corridor does not have a lighting fixture; therefore, it did not represent in the graphs. The maximum consumption is in the living room for the weekdays and bathroom for the weekends in this household.



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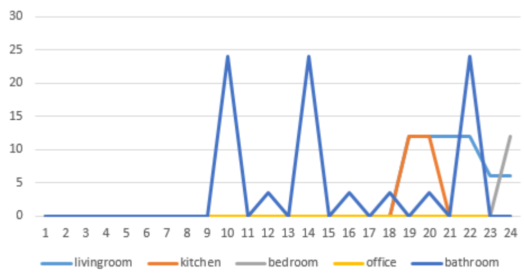


(b)

Figure 4.9 Weekly Lighting Schedule of Household II: (a) weekdays, (b) weekends

4.7 Household Type III

One-family households constitute more than 65% of households. A quarter of these households consist of families with four people, with two children and parents. In household III, a family with parents, a high-school child, and a university student was studied. The house of the family is a 106,5 m2 apartment. According to the post-pandemic conditions, one of the parents is working from home, and the other is regularly commuting to work. The high school child goes to school, and the university student is studied in hybrid education. According to the hybrid system, he/she studies at home in the mornings and attends the afternoon classes in the university.

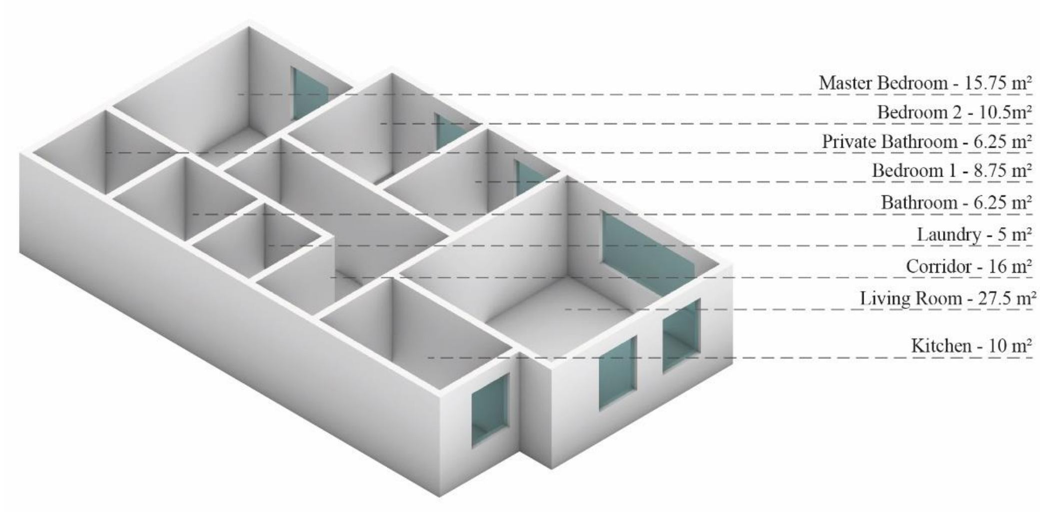


Figure 4.10 Isometric Plan Layout Representation of Case Study-III

Similar to the previous cases, the house is located in Ankara, and simulation was performed 5A climate zone according to the ASHRAE 5A climate zone. The apartment is generated by a living room, three bedrooms, a kitchen, two bathrooms, a laundry, and a corridor. The penetrations are located on the north and east facades of the house.

The heating setpoint is determined as 21°C, and the apartment is naturally ventilated when the outdoor temperature exceeds 22°C.

Table 4.10 General Energy Consumption of Household III

	Area (m^2)	Total Energy (kWh)	Energy per Area (kWh/m^2)	Heating Energy (kWh)	Appliance Energy (kWh)	Lighting Energy (kWh)
Household III	106	9506.3	89.7	3959.6	5323.4	214.3

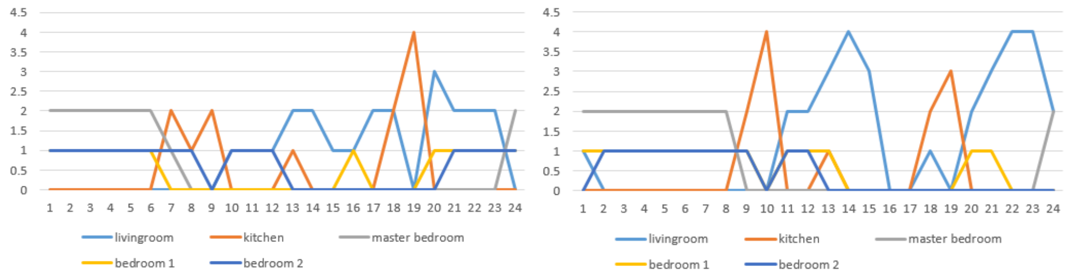
4.7.1 Occupancy Schedule

The occupancy load for each room is determined as ppl/m^2 by the Honeybee. Since the presence of a teleworking parent and homeschooling child, the apartment is occupied every hour on weekdays. The house is fully unoccupied for two hours on weekends. The presence of occupants influences the amount of energy required for heating as well as the use of equipment and lights. The maximum occupant loads of the rooms vary since children have separate rooms.

Table 4.11 Occupancy Load in Each Room for Household II

LR	K	BR	BR 1	BR2
4 ppl	4 ppl	2 ppl	1 ppl	1 ppl
0.15 ppl/m^2	**0.40 ppl/m^2**	**0.13 ppl/m^2**	**0.11 ppl/m^2**	**0.10 ppl/m^2**

According to the focus group study, the living room has the highest number of occupants during the day. Although the number of inhabitants increases during weekends, the movement of the occupants is more active during the weekdays.



(a) (b)

Figure 4.11 Weekly Occupancy Schedule of Household III: (a) weekdays, (b) weekends

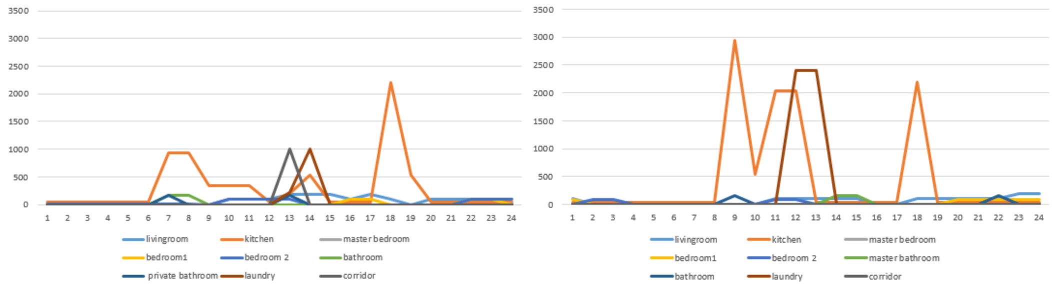
4.7.2 Equipment Schedule

The occupant has determined the existing appliances in each room in the focus group interview. The energy usage of the equipment is determined by using data in Table 4.3. Since the area is extremely small and the equipment energy consumption is high, the laundry room has the highest equipment load in this household case. However, in comparison to the other rooms, the appliances in the laundry have a relatively shorter usage time.

Table 4.12 Equipment List and Load in Each Room for Household III

LR	K	BR	BR 1	BR 2	BA	L	C
TV	Refrigerator	Phone Charger	Phone Charger	Phone Charger	Hair Dryer	Washing Machine	Vacuum Cleaner
Laptop	Dishwasher		Laptop	Laptop		Dryer	
Phone Charger	Oven					Iron	
	Coffee Machine						
	Toaster						
	Microwave						
6.98 W/ m²	**339.80 W/ m²**	**0.25 W/ m²**	**10.75 W/ m²**	**8.95 W/ m²**	**25.60 W/ m²**	**724.60 W/ m²**	**100 W/ m²**

The teleworking parent uses the living room as the office space and increases the energy consumption of the room due to the use of a personal computer during the day. The peak point of consumption occurs for dinner preparation on weekdays. On the weekdays, the difference between the maximum and minimum consumption is relatively less than on the weekend. On the other hand, the weekend peak represents the kitchen during the morning, and the value is almost preserved until 2 pm for housework.



(a) (b)

Figure 4.12 Weekly Equipment Schedule of Household III: (a) weekdays, (b) weekends

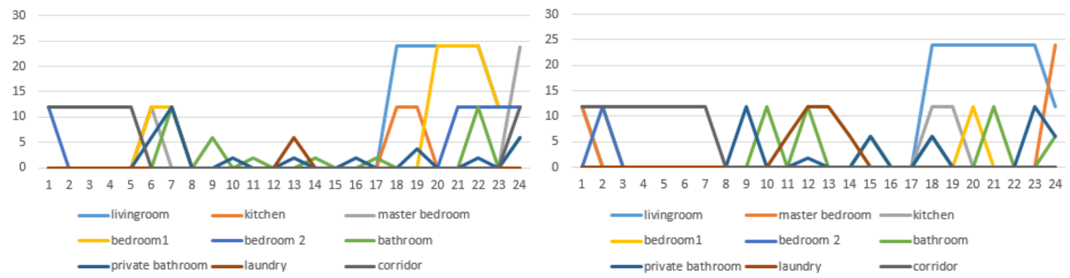
4.7.3 Lighting Schedule

Lighting schedules are the least affected by the Covid-19 pandemic compared to occupancy and equipment schedules since they are only activated during the night. The number of the lighting fixtures is determined according to the household, and the energy consumption is estimated using the LED bulb (12 W).

Table 4.13 Lighting Load in Each Room for Household III

LR	K	BR	BR 1	BR 2	BA	P.BA	L	C
24 W	12 W	36 W	24 W	24 W	12 W	12 W	12 W	24 W
0.87 W/ m²	**1.20 W/ m²**	**2.29 W/ m²**	**2.74 W/ m²**	**2.29 W/ m²**	**1.92 W/ m²**	**1.92 W/ m²**	**2.40 W/ m²**	**2.40 W/ m²**

The presence of an occupant in residence at night is the distinguishing key component for the lighting. During the day, the rooms that require lighting are the bathrooms and laundry. This household's peak lighting usage occurs in the living room during the week. An apparent lighting consumption is in the corridor after midnight. The household uses the corridor lighting as a night light.



(a) (b)

Figure 4.13 Weekly Lighting Schedule of Household III: (a) weekdays, (b) weekends

4.8 Household Type IV

According to the TUIK households research, extended families generate a small proportion and constitute 14% of all household typologies in Turkey. Around 73% of the extended family households include more than six-member. An extended family is studied as household IV in order to observe the impact of the occupant number on energy consumption. The household is composed of two elderly, parents, an elementary school and a high school child. Both parents and children commute to work and school. The house is occupied only by elderly individuals during the day.

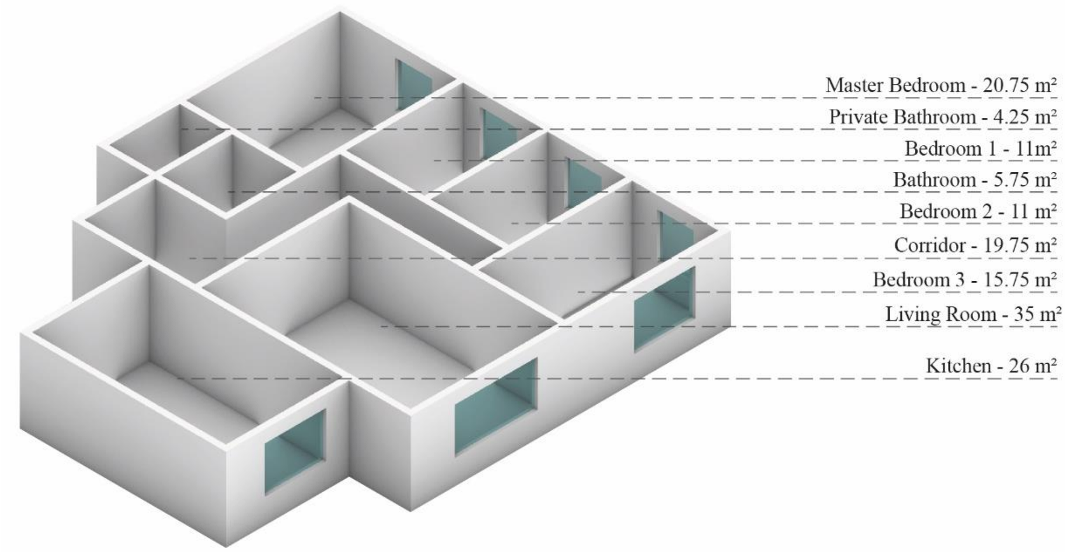


Figure 4.14 Isometric Plan Layout Representation of Case Study-IV

The residence is located in Ankara, Turkey. The ASHRAE 5A climate zone and ASHRAE standards construction materials are adopted for energy simulations. The apartment consists of a living room, four bedrooms, a kitchen, two bathrooms, and a corridor. The facade directions are accepted as the same as the previous case studies facing north and east.

The apartment is ventilated naturally. When the outdoor temperature exceeds 22°C, the windows are assumed to be open.

Table 4.14 General Energy Consumption of Household IV

	Area (m^2)	Total Energy (kWh)	Energy per Area (kWh/m^2)	Heating Energy (kWh)	Appliance Energy (kWh)	Lighting Energy (kWh)
Household IV	149	9518.5	63.8	5576.8	3759.5	182.2

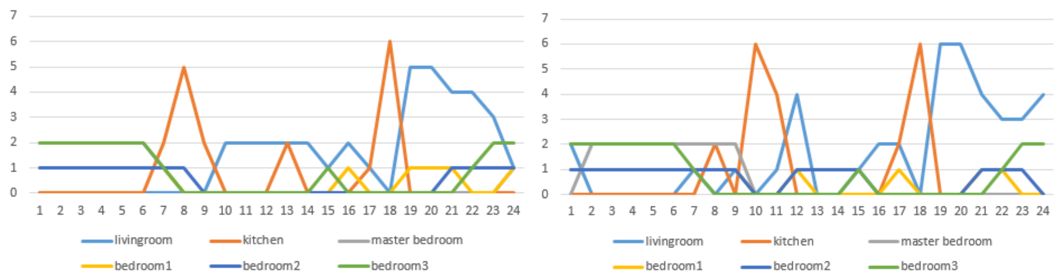
4.8.1 Occupancy Schedule

The house is occupied by relatively more occupants than in previous cases, and the occupancy loads for each room are different. Due to the number and diversity of occupants, the house is always occupied by at least one occupant. The presence of occupants in the dwelling increases the energy need for heating, equipment, and lighting. Appliance and lighting schedules show similarities to the occupancy schedules.

Table 4.15 Occupancy Load in Each Room for Household IV

LR	K	BR	BR 1	BR2	BR3
6 ppl	6 ppl	2 ppl	1 ppl	1 ppl	2 ppl
0.17 ppl/m²	**0.23 ppl/m²**	**0.10 ppl/m²**	**0.09 ppl/m²**	**0.09 ppl/m²**	**0.13 ppl/m²**

The living room and the kitchen are the common areas for the household and represent a dominance in the schedules. The occupancy load is slightly higher on weekends. Since the weekday and weekend occupancy graphs are related, it is possible to deduce that the elderly people do not prominently affect the movement in the house.



(a) (b)

Figure 4.15 Weekly Occupancy Schedule of Household IV: (a) weekdays, (b) weekends

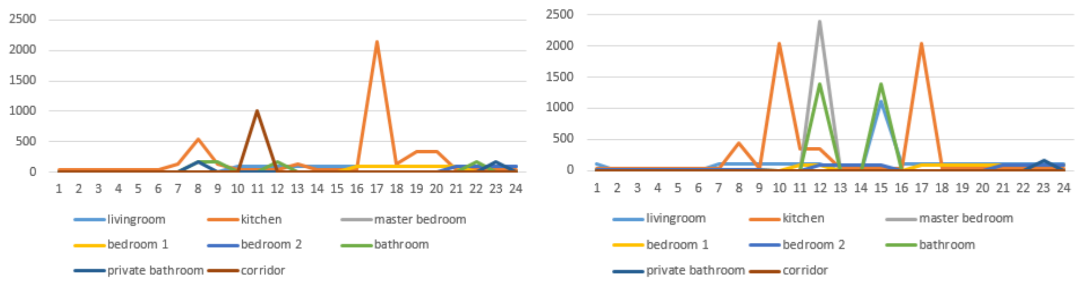
4.8.2 Equipment Schedule

The inhabitants specified the equipment information for each room. According to Table 4.3, the equipment load of the rooms is calculated by the author. Since the usage time of the appliances is changeable, the room loads are only informative with the equipment schedules. In this sense, the bathroom has the highest load rate and consumes 0.64 kW weekly. However, the kitchen consumes 4.5 kW of energy in a week with a lower equipment load. The reason for the inverse relation is the difference between the room areas and the equipment usage schedules. Bedroom 3 does not include any appliances and is excluded in the graphs.

Table 4.16 Equipment List and Load in Each Room for Household IV

LR	K	BR	BR 1	BR 2	BA	P.BA	C
TV	Refrigerator	Phone Charger	Phone Charger	Phone Charger	Washing Machine	Hair Dryer	Vacuum Cleaner
Vacuum Cleaner	Dishwasher	Iron	Laptop	Laptop	Dryer		
Phone Charger	Oven				Hair Dryer		
	Toaster						
	TV						
31.49 W/ m²	**109.08 W/ m²**	**115.58 W/ m²**	**8.55 W/ m²**	**8.55 W/ m²**	**240.52 W/ m²**	**37.65 W/ m²**	**50.38 W/ m²**

Equipment energy consumption is relatively higher on the weekends due to the presence of all households in the apartment. Only the elderly people occupy the house in the daytime during the weekdays. However, according to the weekday graph, there is not a significant consumption between 12 and 16 pm. As a result, elderly people do not represent high energy-consuming behaviors during the day in the dwelling. The housework and the increased number of occupants cause excessive energy use on the weekend.



(a) (b)

Figure 4.16 Weekly Equipment Schedule of Household IV: (a) weekdays, (b) weekends

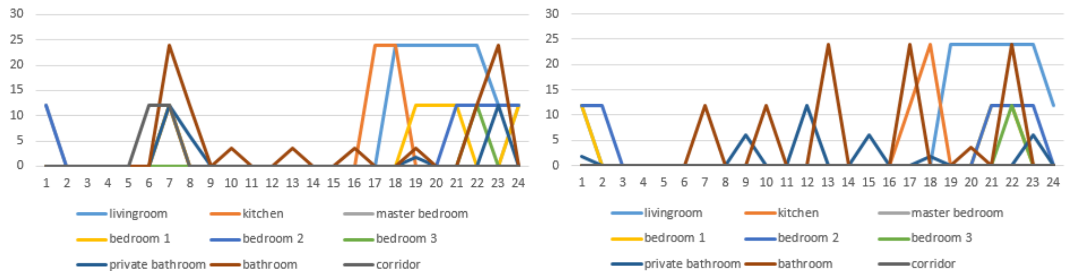
4.8.3 Lighting Schedule

The lighting usage is minimal in comparison to the other household equipment. Also, the improvements in lighting efficiency have resulted in considerable reductions in the amount of energy consumed by lighting. The occupant has only specified the number of the lighting fixtures. Since the user does not indicate information about the kind of illumination, each fixture is accepted as having a LED bulb.

Table 4.17 Lighting Load in Each Room for Household IV

LR	K	BR	BR 1	BR 2	BR 3	BA	P.BA	C
24 W	24 W	24 W	12 W	12 W	12 W	24 W	12 W	36 W
0.69 W/ m²	**0.92 W/ m²**	**1.15 W/ m²**	**1.09 W/ m²**	**1.09 W/ m²**	**0.77 W/ m²**	**4.17 W/ m²**	**2.82 W/ m²**	**1.81 W/ m²**

Due to most households leaving the house early on weekdays and elderly occupants starting the day early, lighting energy consumption starts in the early morning. Only bathroom lighting is used in the daytime. The living room is the room where the lighting is used longest time. Usage of lighting increases parallel to the rise in the number of the household member during the weekends.



(a) (b)

Figure 4.17 Weekly Lighting Schedule of Household IV: (a) weekdays, (b) weekends

4.9 Results and Discussion

There are numerous factors that affect the energy consumption of a residential building, such as "disposable household income, age, gender composition in the household, gender of the household head, education, occupation, marital status, home ownership, household size, number of children, location, cooking habit, availability of fuel alternatives and accessibility, cooking utensils, wage level in the labour market, occupation, house type, number of rooms and size of residence (in m^2) and access to energy carriers."[147] The main research question, "To what extent has the occupants' post-pandemic daily routines changed the energy consumption of residential buildings?" is answered during this chapter.

This study investigates the energy consumption of four different households in terms of heating, equipment, and lighting usage during post-pandemic daily routines. The first household has both teleworking and regular working days, and it can be compared as pre-pandemic, lockdown, and post-pandemic period in itself. The two-day regular working graph represents the pre-pandemic life and behaviors. The house is occupied only between 6 pm, and 8 am. The midday is unoccupied, and as a result,

[147] Luc Vinet and Alexei Zhedanov, "A 'Missing' Family of Classical Orthogonal Polynomials," *ZEW Economic Studies Volume 44* 44 (November 7, 2010): 43, https://doi.org/10.1088/1751-8113/44/8/085201.

equipment energy consumption is minimum, and lighting is not used during the day. The three teleworking days is the simulation of the lockdown period of the pandemic. According to the simulation results, the daily energy consumption of the teleworking day is 2.8 times higher than the regular working day. When evaluating as a week, the case is referenced to the post-pandemic conditions. The weekly equipment energy consumption of the current case is 43% higher than the pre-pandemic period and 20% lower than the lockdown period.

If the case studies are considered similar to the previous example, the second household is an example for the lockdown stage of the Covid-19 since all occupants are teleworking. Household III represents the post-pandemic daily life; the family is a combination of teleworking, distance education, regular working and education. And the last case study shows the pre-pandemic behaviors of occupants in a residential unit. All these comparisons are regardless of the number of people in the households. Therefore, the simulation results have not been analyzed with the prementioned periods assigned to the household cases. All families are modeled and simulated according to the focus group interview on November 2021.

The main factor that affects heating consumption is the area of the house. On the other hand, the difference between household II and III heating energy use can not be explained by the size of the residence. In this case, the higher number of occupants and more use of appliances generates more internal heat gains and decreases heating load. Equipment energy use can be associated with the number of occupants and the duration of occupancy. The reason for the high energy consumption for equipment on household III is the presence of a teleworking parent and homeschooling child.

The effect of the Covid-19 pandemic can be observed between households III and IV. Although the number of occupants and the residence area of household IV is higher than household III, the total annual energy consumption of these cases is quite similar. The high energy consumption for equipment on household III is caused by a home working parent and homeschooling child. Two conclusions can be observed according to this similarity. The first is the impact of the occupancy existence during the day on energy consumption, and the other is the energy-efficient behaviors of elderly people.

According to graphs in household cases, the most frequently used appliances are the lighting, but the lighting energy consumption is too low to make a comparison.

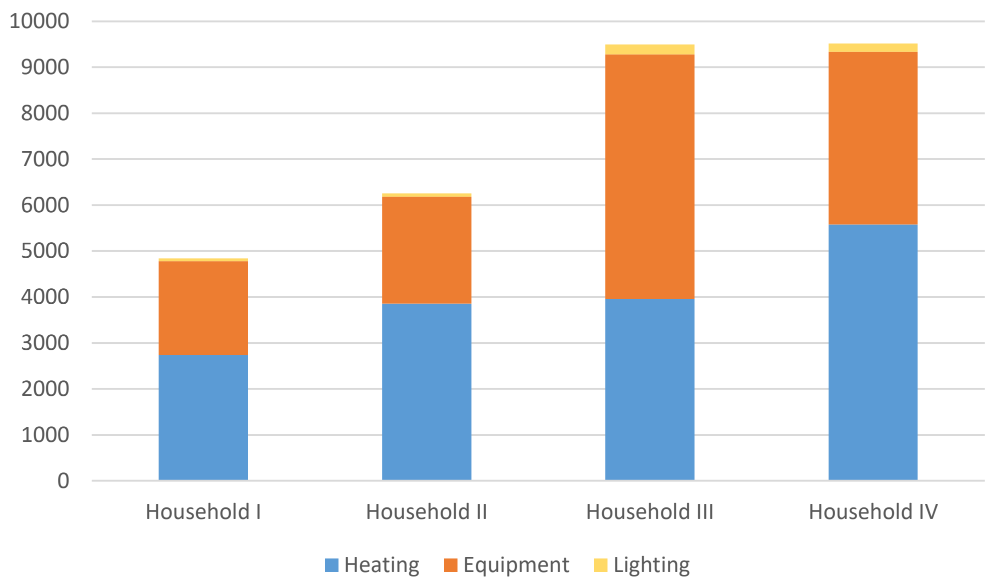


Figure 4.18 Energy End-Uses of Households

The energy consumption for each person decreases as the number of occupants increases. However, this assumption is not valid for the per area calculations. According to Figure 4.20, the total energy consumption per area of households with home office workers (household I, II, and III) is higher than the households with regular employees and students that is household IV. According to simulations, no direct relationship was observed between the size of the residence and equipment energy consumption.

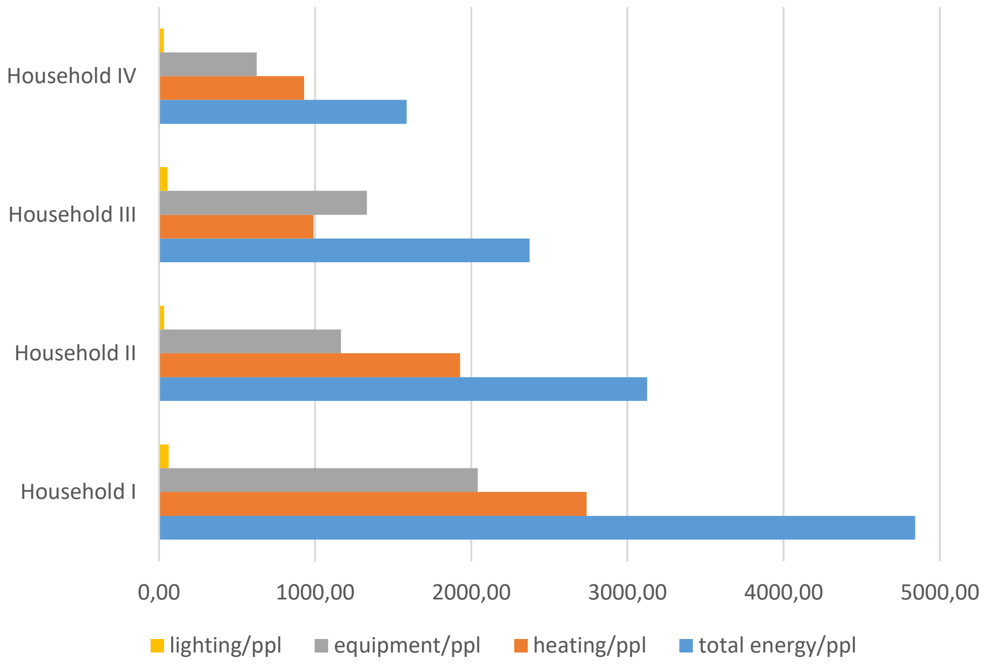


Figure 4.19 Energy Consumption per Occupant

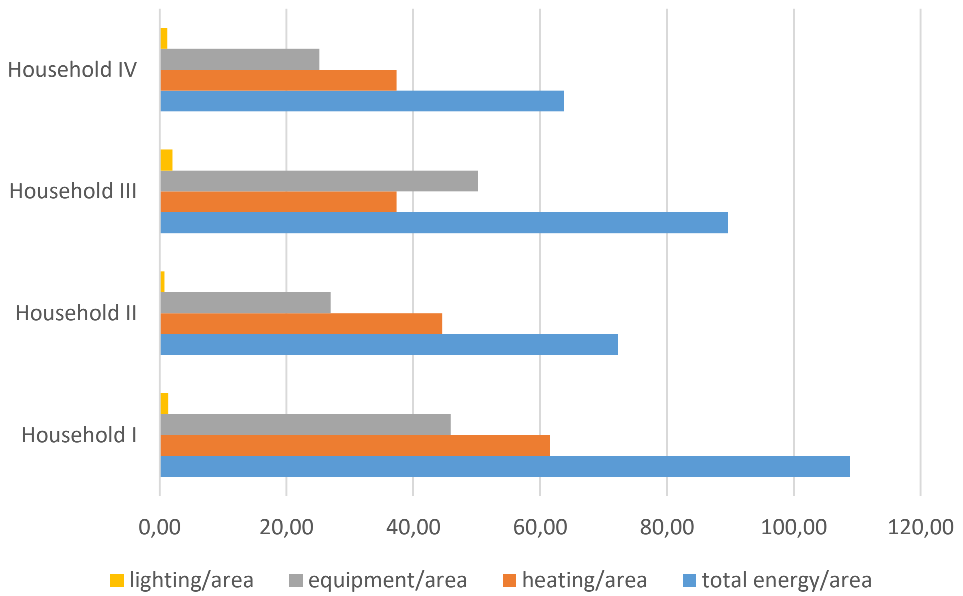


Figure 4.20 Energy Consumption per Area

How did post-pandemic conditions change the energy-related routines of the occupants?

The level of income is found to be positively related to the rate of consumption. Although high-income and highly educated households are more conscious about energy efficiency and sustainability, they consume more electricity due to the more usage of multiple types of appliances compared to other households. According to Brom et al., as an exception, single-person households with a high income have the lowest average energy consumption.[148] They explained this result with the possibility of spending less time at home compared with other household types. Although the existing case studies represent the high-income group, the influence of the pandemic can be observed as the increased time of dwelling usage.

Also, people owned more appliances to satisfy their entertainment needs at home since all outdoor entertainment places were unavailable during the lockdown. As a result, people still spend more time at houses than before, and the usage change increases the energy consumption at residences.

How does the size of the dwellings affect the energy consumption per area?

The study shows that total energy needs increase when the size of the house increase. The size of the dwelling affects only the heating energy need. The heating setpoint is assumed as 21°C in all cases. Therefore, the main difference in heating energy needs is caused by the internal heat gains from occupants, appliances, and lighting. According to graphs, the influence of these factors is less than the size of the dwelling since total heating energy need increases from household I to household IV. However, the per area graph represents the decrease of heating energy need per area when the total area of the house increases. The internal heat gains can explain the difference between households.

[148] van den Brom, Meijer, and Visscher, "Performance Gaps in Energy Consumption: Household Groups and Building Characteristics."

How does the number of household members affect the energy consumption per person?

Previous studies show that single-person households are more frequent in the low energy-consuming group, while two-person households are usually in the high energy-consuming group.[149] The total energy consumption affirms the previous researches. However, the total energy need for per person apparently increases when the number of household members decreases. According to the simulation results, the energy consumption per person in a single-person household is three times that of a six-person household. The teleworking or distance learning member influences the sub-categories of heating, equipment, and lighting use.

What is the relationship between heating, appliance, and lighting energy use according to the type of household?

The location of the households is in Ankara; therefore, a significant heating energy need is expected to be observed in the performance simulations. The primary energy consumption of households I, II, and IV has resulted in heating need. On the other hand, in household II, the equipment energy use is 35% more than the heating energy use. One of the reasons is that there is more equipment in the house than on average. Also, the presence of teenagers in the dwelling has an important impact on equipment energy consumption.[150] And finally, the use of work-related appliances have caused unexpected result. The lighting energy consumption does not provide sufficient data for analysis.

[149] Ibid.
[150] Ibid.

How did teleworking and distance education influence the energy consumption in dwellings?

Household I, II, and III have teleworking or distance learning members. The main influence of teleworking and distance education is the increase in appliance usage. In the first household, the total energy consumption of the home working days is more than twice that of the regular workdays. All members of household II and half of household III occupy the house on weekdays for working or learning. The main difference between these houses is caused by the equipment used. The teleworking parent in household III also does housework and uses high-energy consuming appliances. However, the usage pattern of the same appliances in household II is less frequent since the number of members is fewer, and there is the non-existence of teenage or child members.

How can the role of occupant behavior in energy consumption be understood by evaluating the specific household types and building characteristics?

This study analyses four types of households in different dwellings. All dwellings are apartment houses with a different plan layout. Further studies are needed to consider more characteristic features of residences. The differences in the simulation results are only caused by the behaviors of the occupant since all other variables are accepted as constant for each case. The findings of this study are expressive for the defined focus group and provide a better understanding of the influence of the occupant on energy consumption in residences.

This thesis represents the following results with reference to the studied households;

- The number of occupants does not directly change the total energy consumption.
- The size of the residence has an impact on heating energy use; however, no direct relationship was observed with equipment and lighting consumption.
- The presence of home office or homeschooling occupants has a distinguishable impact on daily energy use.

- The effect of elderly individuals on total energy consumption is minimum compared to other occupants. This can be explained by the limited appliance usage of these members.
- Since the increased efficiency of lighting, the energy need for lighting is considerably less than heating and equipment energy usage.
- Kitchens consume most of the equipment energy in a residential unit due to equipment density.
- The heating energy consumption of the hall is the highest in all residences since it has the largest area.

As a result of the study, the essential component in characterizing energy consumption is the number of occupants in residence. The energy consumption increases as the number of occupants increase. However, the increase is not directly proportional. Energy usage per person represents an opposite correlation. As a result, it is possible to express that the households with more members are more energy efficient.

In conclusion, this study investigated both the total energy consumption of residential units through schedules and the effect of each space, occupant, and appliance on buildings' energy consumption. The performance simulations are a simplification of the reality. A detailed understanding of occupant behaviors is significant for energy efficiency studies in architecture and building science.

CHAPTER 5

CONCLUSION

The conducted literature review represents the importance of human-building interaction in terms of the energy performance of the buildings. Occupants and occupant behavior is described as the unpredicted factor for the buildings' energy consumption. This study included the occupancy schedules to the energy simulations to observe their effect and decrease the performance gap mentioned in the literature.

The effects of the Covid-19 pandemic may last for an extended period of time. Although the impact of the pandemic on daily life has been reduced, sustained consequences on behavioral patterns may be seen in social life. People prefer to spend time either in their homes or open-air spaces. As a result of the pandemic's impacts on buildings, there should be a new knowledge of design and environmental systems to correspond to the new lifestyles. The thesis introduce occupants as the human building interaction objects and aims to predict more accurate result by introducing various schedules to performance simulations.

TUIK household study is very significant for the thesis. The case studies were determined according to the dominant household types in the data. Real households that are suitable to the selected types were found, and information about their daily lives and the residential unit was obtained through interviews. In reference to the interviews, occupancy, equipment, and lighting schedules were created and simulated in the BPS tool Energy Plus.

The purpose of this study is to explore the impact of different households’ energy consumption during the post-pandemic lifestyle in terms of heating, equipment, and lighting energy consumption. Three different schedules are integrated into the BPS in order to evaluate the energy consumption results. Four different household types are analyzed in the case studies. According to the results of this study, analyzing specific household types helps to understand better the effect of the occupant on actual energy usage and an efficient technique to observe the impact of inhabitants on residential energy usage.

This thesis mainly focuses on the occupant schedules of residential environments, rather than office buildings which are mostly studied according to the literature of the energy research and schedules. The goal of the study is to understand the current relationship between living and working environments under the Covid-19 conditions. In this thesis, the post-pandemic occupancy schedules of family types were examined. The presence of home working and homeschooling members are simulated to evaluate the changes in the post-pandemic conditions. The post-pandemic schedules have increased the total amount of energy used and changed the most energy-consuming hours during the day in residential units. Since sustainability is a significant feature in architecture, architects, engineers, and policymakers should consider the current loads in the residential buildings. A detailed understanding of how occupants actually use energy is required for the responsible actors to increase the efficiency of energy-saving methods.

According to the results of the study, the essential component in characterizing energy consumption is the number of occupants in houses. The energy consumption increases as the number of occupants increase. However, the increase is not directly proportional. Energy usage per person represents an opposite correlation. As a result, households with more members are more energy efficient.

In reference to the other research about occupant energy consumption in the literature, studying with larger dataset results in more accurate predictions on energy use. This information may be used to conduct comprehensive calculations for recent and emerging architectural projects.

5.1 Limitations of the Study

The thesis is subjected to some limitations that need to be addressed. The first limitation of the study is the generalization of the results. The size of the focus group is highly limited to acknowledge information about the society. Also, in order to obtain accurate and comparable results, the focus group is mainly restricted with the limitation of education level, employment status, income group, and location information. Since the interview is required personal information and representation of behaviors, enlargement of the study group is voluntary. The data process of each household requires an intense study on interview results.

Although the study is investigated energy behaviors of different households during the post-pandemic period, the absence of pre-pandemic or strict lockdown energy information is complicated to understand the value of the study. The Covid-19 is a long period to gather data from a household without changes that will affect the energy consumption. The description of each day in a week creates an enormous workload, and the daily differences are negligible. Therefore, the weekend and weekdays separation is used as a generalization of the occupant behavior distinction.

Secondly, some assumptions were needed to equilibrate the household case studies. The facade direction of the residence, construction materials, window sizes, heating energy source, the floor of the dwelling, cooling system, heating set point, and appliance models are accepted as the same or at least similar to avoid inconsistencies that may occur from these differences. The building performance model did not calibrated, since the focus of the study is the effect of different households rather than the performance gap.

The Honeybee is a Grasshopper plug-in that works with the Energy Plus performance simulation tool. The plug-in has a friendly interface; however, it has some limitations. The residential building type has no subcategories for different rooms. As a result, some properties are manually defined to the assigned rooms. The Honeybee results in some unexpected errors that influence the simulation results.

Therefore, the results need to be analyzed before the data transformation in order to prevent any inconsistency due to errors. Even though the mentioned limitations, the study enhances the understanding of energy-related occupant behaviors in households.

5.2 Suggestions for Further Studies

The current study has identified several research problems on energy-related occupancy behavior in residential buildings. However, the subject is a complex, multivariable and multidisciplinary field of inquiry. Future research into the interrelationship between different energy behaviors of occupants is needed to construct more precise predictions in energy performance assumptions.

More work with larger sample sizes and data is required to increase the accuracy and reliability of the simulation results and the generalization of the outcomes. The simulation methods can be developed with the advanced usage of BPS tools. Even though fundamental modeling techniques are sufficient for the purpose of the study, the method used for modeling occupancy schedules would be enhanced with comprehensive and advanced methods such as agent-based and stochastic models.

And finally, two methods can be suggested to make a comparative analysis. First is examining electricity and heating bills covering the pre-pandemic and post-pandemic periods with the simulations. Secondly, conducting case studies based on longer durations and regular interviews enables comparisons between periods.

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APPENDICES

A. Weekday Occupancy Schedule and Load Calculations

hours	room 1	room 2	room 3	room 4	room 5
1	0	1	1	1	0
2	0	1	1	1	0
3	0	1	1	1	0
4	0	1	1	1	0
5	0	1	1	1	0
6	0	1	1	1	0
7	0	0.5	0	1	0.5
8	0	0	0	1	0.25
9	0	0	0	0	0.5
10	0.25	0	0	1	0
11	0.25	0	0	1	0
12	0.25	0	0	1	0
13	0.5	0	0	0	0.25
14	0.5	0	0	0	0
15	0.25	0	0	0	0
16	0.25	0	1	0	0
17	0.5	0	0	0	0
18	0.5	0	0	0	0.5
19	0	0	0	0	1
20	0.75	0	1	0	0
21	0.5	0	1	1	0
22	0.5	0	1	1	0
23	0.5	0	1	1	0
24	0	1	1	1	0
max capacity	4	2	1	1	4
	room 1	room 2	room 3	room 4	room 5
m2	27.5	15.75	8.75	10.5	10
ppl/m2	0.15	0.13	0.11	0.10	0.40

B. Total Equipment Load of Each Room

m2	27.5	15.75	8.75	10.5	10
	room 1	room 2	room 3	room 4	room 5
	98	4	90	90	38
	90		4	4	300
	4				2000
					500
					400
					160
watt	192	4	94	94	3398
watt/m2	6.98	0.25	10.74	8.95	339.80

C. Weekday Equipment Usage Schedule

hours	room 1	room 2	room 3	room 4	room 5
1	0	1	0.04	0.04	0.01
2	0	1	0.04	0.04	0.01
3	0	1	0.04	0.04	0.01
4	0	1	0.04	0.04	0.01
5	0	1	0.04	0.04	0.01
6	0	1	0.04	0.04	0.01
7	0	0	0	0.04	0.28
8	0	0	0	0.04	0.28
9	0	0	0	0	0.10
10	0.47	0	0	0.96	0.10
11	0.53	0	0	0.96	0.10
12	0.53	0	0	0.96	0.01
13	0.98	0	0	0.96	0.06
14	1	0	0	0	0.16
15	1	0	0	0	0.01
16	0.47	0	0.96	0	0.01
17	0.98	0	0.96	0	0.01
18	0.51	0	0	0	0.65
19	0	0	0	0	0.16
20	0.51	0	0	0	0.01
21	0.51	0	0	0	0.01
22	0.51	0	0.96	0.96	0.01
23	0.51	0	0.96	0.96	0.01
24	0	1	0	0.96	0.01
max capacity	192	4	94	94	3398
	room 1	room 2	room 3	room 4	room 5
m2	27.5	15.75	8.75	10.5	10
watt/m2	6.98	0.25	10.74	8.95	339.80

D. Weekday Lighting Usage Schedule

hours	room 1	room 2	room 3	room 4	room 5
1	0	0	0	0.5	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0.33	0.5	0	1
7	0	0	0.5	0	1
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0
13	0	0	0	0	0
14	0	0	0	0	0
15	0	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	1	0	0	0	1
19	1	0	0	0	1
20	1	0	1	0	0
21	1	0	1	0.5	0
22	1	0	1	0.5	0
23	0.5	0	0.5	0.5	0
24	0.5	0.66	0.5	0.5	0
max capacity	24	36	24	24	12
	room 1	room 2	room 3	room 4	room 5
m2	27.5	15.75	8.75	10.5	10
watt/m2	0.87	2.29	2.74	2.29	1.20