IoT Based Climate Control Systems Diffusion in Intelligent Buildings - A System Dynamics Model

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Abstract. The urbanization trend and the prevailing energy crisis in India, makes it important to study the potential of IoT technology in the Indian buildings market. This research work proposes a systems dynamics model of IoT based climate control systems diffusion in Intelligent Buildings. The modeling process leverages the generic Bass model of technology diffusion and augments it with causal loops based on the enablers and barriers to IoT diffusion in buildings identified through literature review. The model encompasses the technological, social, financial, business, regulatory and environmental aspects of the system, and uses stock-flow concepts to represent their dynamic interplay. The model will be useful to value chain players in the construction sector by providing them support for strategic decision-making concerning market entry and new product development. It will also help policy makers to assess industry readiness to tackle the prevailing energy crisis and devise strategies to mitigate it.

Keywords: Internet of Things, Smart Buildings, Energy Efficient Comfort, Technology Diffusion, System Dynamics

1 Introduction

Modern Buildings consume over 40% of worldwide energy, and a major portion of this is for managing occupant comfort [1]. About 80-85% of the total energy consumption is from the use-phase of the building, where occupancy related loads such as air-conditioning and lighting play a major role [2]. In recent decades, there is a growing attention towards sensors and controls in buildings, contributed by the intelligent building (IB) initiatives across the globe. In the United States of America, 6% energy consumption reduction in commercial buildings is estimated through building control systems [3]. In India, the real estate sector that comprises four sub sectors, viz., housing, retail, hospitality, and commercial construction, is expected to reach a market size of US$ 1 trillion by 2030 and contribute 13% to the country's GDP by 2025 [4]. India's electricity consumption is growing at the rate of 8–10% per year and is about 4% of the world's total consumption. India's total energy shortage is estimated to be 9% and the peak demand is likely to be 323 GW by 2022 and 437 GW by 2027 [5]. Now, when there is an energy crisis and economy crunch, it is essential to provide a comfortable ambience within buildings, with not only less energy expenditure but also more of intuitiveness to suit occupants' needs.

Currently, the IoT technology for climate control is looked upon to improve energy efficiency in IBs. Despite the promising nature of the technology, the diffusion of information and communication technologies (ICT) is sluggish in construction industry [6]. The IoT industry is showing several positive trends such as sensors price reduction, big data handling ability [7] and higher speed data transfer [8] with the potential to change this situation.

In this direction, system dynamics has been leveraged to understand the time-dependent behavior of this IoT diffusion in the Indian construction industry. System dynamics is a computer aided simulation approach to solve dynamic complex problems involving technological, social, economic, regulatory and business systems [9, 10]. For forecasting technology adoption, system dynamics plays a vital role in assessing uncertainties and gaining insight into various aspects, viz. causal factors and potential diffusion patterns, and thereby supports sound decision making for strategic planning [11]. Most of the ICT / IoT adoption literature in IBs assume a static system, and are deficient in dealing with time-dependent dynamic aspects of adoption. In India, a complex interaction between technology, value chain, policy makers and consumers exist. This is hitherto unexplored to improve technology diffusion. Further, the economic fluctuations, IoT industry growth, booming consumer acceptance of smart phones, etc., contribute to the dynamic aspect of technology diffusion. In this paper, system dynamics is used to model the diffusion of IoT based climate control systems in IBs in India.

1.1 IoT in Intelligent Buildings

According to AlWaer and Clements-Croome (2010) "a sustainable intelligent building can be understood to be a complex system of interrelated three basic issues – People (owners; occupants, users, etc.); Products (materials; fabric; structure; facilities; equipment; automation and controls; services); and Processes (maintenance; performance evaluation; facilities management), and the inter-relationships between these issues [12]." IoT, a technological frontier of ICT, is instrumental to meet the following objectives of IBs.

1. Maximizing the technical performance, investment and operating cost savings, and flexibility [13].
2. Learning capability, self-adjustability, and the relationship between occupants and environment [14].
3. Energy-intelligent concept and satisfying occupants' need with high energy efficiency [14].

Historically, the benefits obtained from relocation flexibility, localized comfort and energy savings have driven wireless sensors' deployment in buildings [15]. Presently, Building Management System (BMS), a computer-based control system, is addressing the needs of comfort and energy management through monitoring and control of subsystems such as air-conditioning, lighting etc. BMSs consist of the following building blocks: 1. Sensors for collecting indoor environment data, 2. Controllers for climate parameters actuation, 3. Communication hardware and the protocols, and 4. Dashboard. IoT enabled BMS would imply the following advancements to the system stated above [16, 17]: 1) Multi-system integrated functions e.g. energy, camera monitoring etc., 2) IP based wireless communication, 3) Remote access to the building subsystems, 4) Cloud based big data processing, 5) Edge devices for fog computing and data visualization, 6) User (includes occupant) engaging applications, 7) Connectivity to personal mobile devices gathering location data and type of activity promoting people centric sensing, a unique selling proposition.

1.2 System Dynamics (SD) application in Technology Diffusion

Innovation diffusion models suggest that pioneers (innovators) are the first group that adopt the technology and they are followed by imitators, who exist in different levels of the product life cycle. Therefore, the main dynamics are derived from three feedback loops, viz. adoption by innovation, adoption by imitation and adoption by market potential [9]. An overview of the literature on the use of system dynamics for modeling technology adoption/diffusion is presented in figure 1 below showing the timeline. The papers on dynamic models of IoT adoption are presented subsequently.

From the literature review, it is evident that the past decade has seen an increase in application of system dynamics model in the technology adoption studies. Adoption of digital technologies such as RFID, IoT, ICT and fiber technology etc. are being addressed in the recent literature. Most of the literature pertaining to adoption of IoT, study the technology related factors and their static nature. Models that concern dynamics are limited in scope and are predominantly case study based, without adequate scope for generalizability.

While it is evident that SD is suitable for studying IoT adoption in IBs, available studies have examined specific aspects, viz., personal, social, technological, regulatory, financial, environmental and business, separately and often without paying attention to the complexities involved due to their interactions, and the consequent dynamics. Hence, there is a clear need to examine IoT adoption in IBs holistically to gain a comprehensive understanding of the phenomenon. The System Dynamics method, being founded on the principles of the Systems Approach, facilitates holistic modeling and analysis. Given (a) the very sharp increase in public and private construction and infrastructure, (b) the corresponding rise in energy consumption coupled with acute energy shortages, and (c) the booming nature of the digital ecosystem in India, SD modeling can benefit stakeholders in the buildings industry and policy makers immensely.

Specifically, this paper attempts to fulfill the following objectives:

a) Categorizing the causal factors identified in the literature as affecting IoT diffusion rate in IBs;

b) Depicting the integrated influences of the causal factors on IoT diffusion rate in IBs using the common SD causal loop diagramming method.

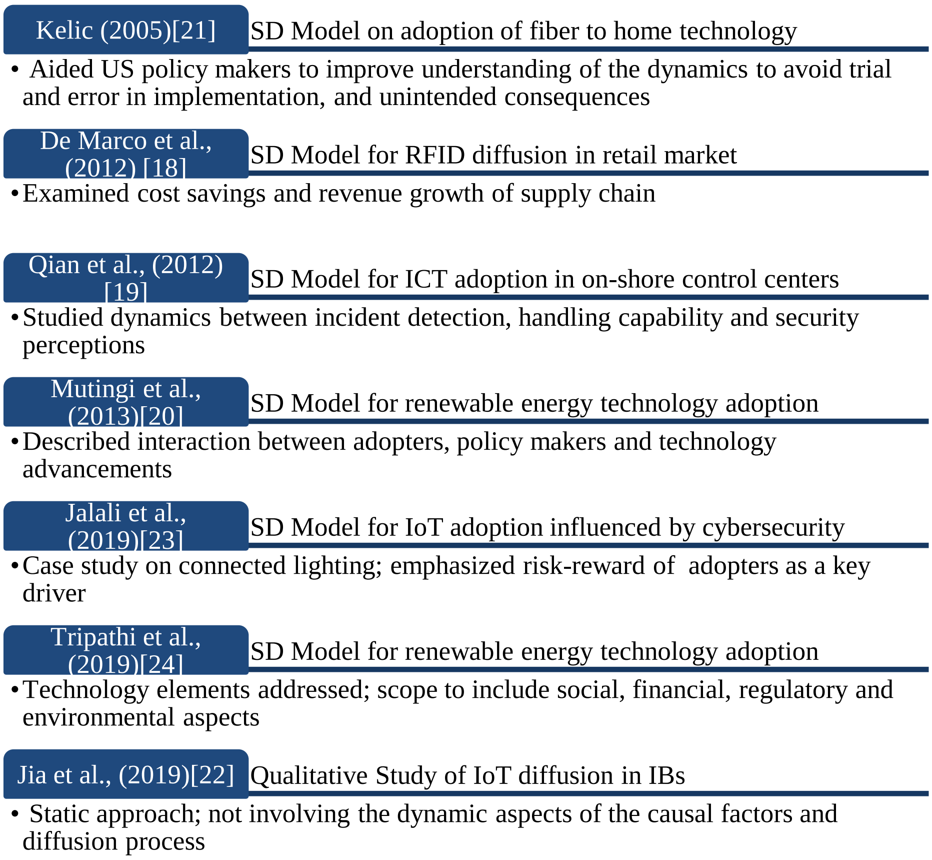

Fig. 1. SD model applied to Technology Adoption in relevant areas.

2 Methodology

The methodology for fulfilling the objectives involves two steps, viz., (1) Developing a basic SD model based on Bass diffusion theory, and (2) Enriching the model with multiple, relevant feedback loops based on literature. The causal loop diagramming method commonly used in SD is employed here.

The basic SD model is developed using the Bass diffusion theory and consists of: a) Two conceptual entities ‘adopter’ and ‘potential adopter’, b) a ‘function’ called ‘adoption rate’, c) a causal loop between the current adopter and the adoption rate driven by factors that govern early adoption, d) a causal loop between the potential adopter and the adoption rate influenced by factors that govern the imitation phenomenon.

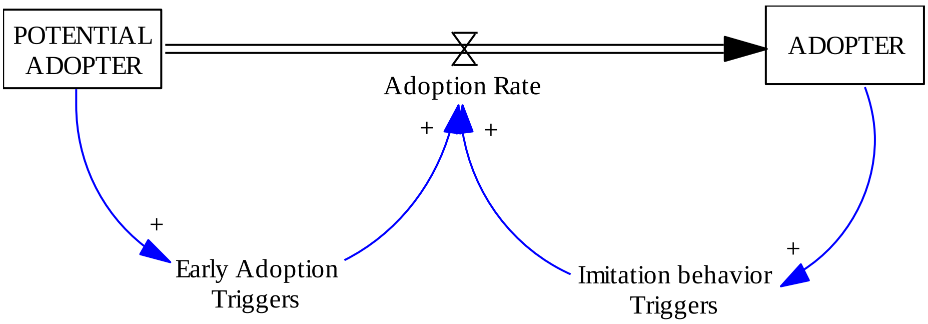

Fig. 2. Basic SD Model for technology diffusion

2.1 Early adoption loop - 'Simulations on Building Performance'

During the design stage, simulations are commonly used for driving the adoption of building monitoring and control solutions, and forecasting energy performance of and comfort levels in a building. Most often, these simulations are used to evaluate if a building will meet certain regulatory standards. ASHRAE 90.1 mandated the use of building energy simulation results to rate building energy performance. Other rating systems, such as Leadership in Energy and Environment Design (LEED), follow the same protocols like ASHRAE 90.1 for energy performance rating, and in addition they require comfort simulations such as day lighting and natural ventilation [25]. With a view to promote low energy buildings in order to meet greenhouse gas reduction targets, other government bodies like European Energy Performance of Buildings Directive (EPBD) also require deploying simulation software for building design and operation [26]. Further, to ensure the validity of such simulations, the US department of energy has carried out in-situ studies of certified buildings in the USA. The utility electricity bills collected were compared with the energy ratings issued based on the baseline energy performance predicted by the simulations. The field data showed 1% less consumption than the modeled value, however with a wide variance around the mean [27].

The early adopters in India are found to prefer simulation models during the building concept stage to ascertain if the building design will meet the comfort needs, while minimizing energy expense. Post construction, there is interest to measure the energy savings and comfort conditions with sensors to ensure that the computer models would be actually right. Model driven IoT value prediction is a causal factor that can impress the early adopter in the buildings market. Such early adopters also expect that these models are accurate and that the comfort and energy predictions come close to reality during the operation phase. Therefore, our SD model considers an early adopter loop that incorporates the value from energy, comfort and lifecycle energy simulations and their delivery time.

2.2 Diffusion Barrier Loop - 1. Technology Uncertainties Related

According to Brachman (2013) [28], technical challenges include plurality of devices (from various producers, with different communication modes), scalability (protocols compatibility), wireless communication reliability, power hungry devices, data security and privacy etc. According to Bajer, (2018) [17] uncertainties in this area mainly include the data silos. Each vendor's software platform using their own cloud may lead to duplicating the nodes, increasing expenditure. Further, large IoT Players tend to introduce proprietary protocols, leading to poor interoperability between sub-systems. Therefore, our model considers device plurality (scalability), data silos, reliability, data security, sensing accuracy and energy consumption of sensing devices etc., as factors in the feedback loop.

2.3 Diffusion Barrier Loop - 2. Financial Impact Related

In India ICT/IoT is seen as a high cost addition during the construction phase and customers are afraid of the costs associated with digital platform switch-overs [6]. In addition to sensors for localized comfort, the actuators increase the cost of the system, making it economically unadoptable [29]. Also, IoT system deployment involves increased installation costs along with the unforeseen upgradation costs. Moreover, unknown costs such as BMS licensing fee are also a concern. This has been a discouraging factor in adopting this technology [30]. Therefore, our model considers factors of risk-return ratio from both capital cost and recurring cost fronts in the feedback loop.

2.4 Diffusion Barrier Loop - 3. Personal and Social Impact Related

User Involvement has been seen as a major factor in technology adoption [31]. It is being realized that human perception and understanding is a primary requirement for successful adoption of ICT/IoT in targeted fields. In the context of climate control systems, occupant engagement through smart phones and other such devices pose a good opportunity [32]. However, when plenty of devices are connected to various networks, privacy and security can be a major concern. While there is provision to protect privacy of every individual, there could be a perception risk that affects trust. This has been reported to influence technology adoption and has a role to play in uncertainties surrounding this technology [33]. Also, predicting occupant activities accurately [29], and engaging by sound user experience designs [34] are essential in this context. Therefore, our model considers privacy concerns, data security, predictability of occupant activities and user experience level as factors in the feedback loop.

2.5 Diffusion Barrier Loop - 4. Environmental Impact Related

One of the key factors affecting the environment in relation to IBs is the battery life of electronics, which require frequent replacement. Studies suggest that, on an average, more than 200 million battery changes can happen every day, world-wide [35]. In addition, presence of abundant sensors in low energy buildings can result in higher embodied energy, affecting life cycle energy cost [36]. Therefore, our model considers impact on buildings life cycle energy and battery replacement scale as factors in the feedback loop.

2.6 Diffusion Barrier Loops - 5. Business Proposition and 6. Regulatory Related

IoT startups are struggling with creating grounded business cases in IBs [17]. Lack of win-win business models can result in poor customer acceptance [37]. Further, industry specific challenges include, (a) Plenty of standards, (b) Construction sector not pulling innovations rapidly, (c) Concerns on norm changes, (e) Lack of information flow across the value chain, etc. [38]. To add, the absence of government incentives has also been seen as a major hurdle [39]. Therefore, our model considers industry speed of accepting new technology, business model effectiveness, profitability etc., as factors in the technology diffusion risk feedback loop. Further, from the regulatory angle, concerns on norm changes, standards count, and lack of government incentives have been considered as risks [38] and included in a feedback loop.

3 The Integrated Conceptual Model – A Discussion

By combining individual feedback loops with the basic Bass diffusion model, the integrated SD model results. The model involves an early adoption loop and multiple risk feedback loops in effect. Figure 3 below describes this model.

The early adopter feedback loop is characterized by the value of the building performance simulation. The imitation behavior is characterized by the word of mouth of early adopters, system integrators and consultants who worked with them.

The positive word of mouth is influenced various risk loops such as technology risk, sustainability and regulatory risks etc. It is to be noted that the causal loops could involve interdependence and mutual interactions. For example, the ability of technological factors to influence occupant acceptance might gain momentum in future. In other words, IoT can precisely gather occupant behavior, through the edge devices that are possessed by the occupants. Also, when the financial and regulation loops are examined, government incentives, if issued, may reduce the financial burden on the first cost for building owners. When the sustainability and technology feedback loops are examined, it becomes clear that self-powered IoT devices are the need of the hour, or else the scale of battery replacement could be of immense negative impact to sustainability. When technology and financial loops are examined, elimination of information silos lead to reduction of first costs. Such loop combinations are depicted in the figure 3 above.

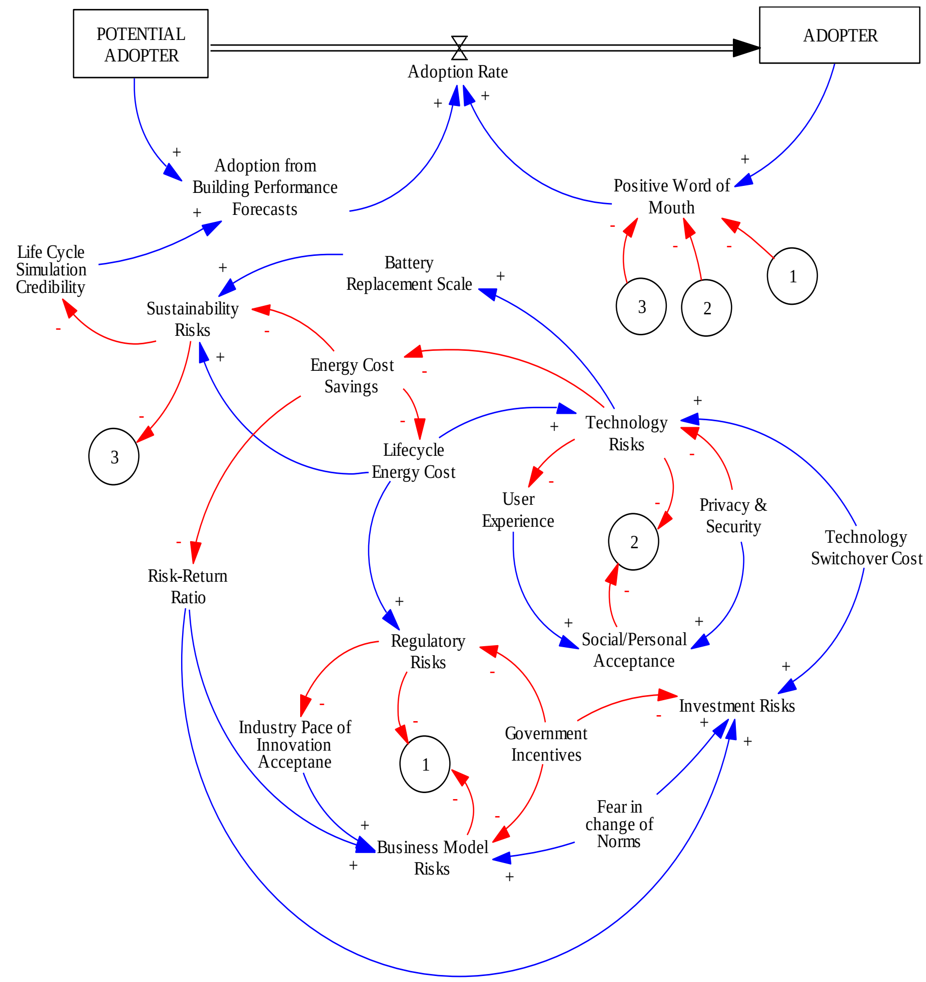

Fig. 3. The Integrated Conceptual Model (Only interaction variables and their causal loops are shown)

Out of the multiple loops, generating demand generation potential, by blending technology and user centricity seems to be the first and foremost risk to be retired. This can be made possible through sound business models that do not burden the customer in terms of cost. Revenue sharing type of models, wherein IoT firms receiving margins from the actual energy savings of a building, not only reduces first cost for the building owner, but also gives trust in the value proposition.

There could be potential limitations to this model. As the factors are brought in from multiple international sources, their relevance to Indian conditions may vary. For example, fear of regulation changes in India could be low, and the privacy perception of occupants could be low. On the other hand, the demand for government incentives could be increasingly higher. Also, certain other practices/trends in India deserve critical attention: 1) For example, building performance simulations in India are performed for getting regulatory clearance, but proper comparisons with real building data does not exist. Reforming this behavior in the value chain can bring out the real benefits of monitoring comfort and energy, 2) With the rapid sprouting of IoT startups, application interfaces that handle device heterogeneity can be developed faster and cheaper. Along these lines, there could be more unknown factors that are India-specific and have higher relevance. They have to be dug out for the effectiveness of the forecast.

This paper is an early attempt to integrate, using various literature sources, multiple factors that contribute to the diffusion of IoT in the Indian scenario, and focus on the dynamic aspect of diffusion/adoption, by leveraging SD modeling.

4 Conclusion and future directions

A conceptual model that is essential to predict the dynamic behavior of IoT diffusion in the Indian IB market has been developed. It covers system level aspects from multiple fronts such as technological, social, financial, business, regulatory and environmental, and leverages stock-flow concepts to represent the dynamic behavior. Managerially, this model should aid value chain players in strategic decision making for entering the IB market or to develop new products. It also aids policy makers to assess industry readiness to tackle the prevailing energy crisis and to devise strategies accordingly. Theoretically, this model includes addition of dynamic behavior of IoT diffusion to the current body of IB literature that has focused much more on the static aspects.

In future, the relevance of each causal factor in terms of severity and occurrence will have to be identified through appropriate qualitative and quantitative research techniques such as interviews, group discussions, participative ranking etc. If there are India-specific causal factors that are not identified in this process, they will have to be brought out through expert interactions. Such data collection will form the input and boundary conditions for solving the model. Also, multiple what-if loops that explain the interaction between risk categories can elucidate various resultant scenarios of diffusion/adoption hurdles. Also, interdependence between multiple risk categories will have to be investigated for potential time delays. There could be special scenarios such as technology and regulatory forces relying on each other continuously resulting in a circular causal loop calling for policy interventions.

5 References

1. Pérez-Lombard, L, Ortiz, J., Pout, C.: A review on buildings energy consumption information." Energy and buildings 40(3) 394-398 (2008).
2. Cabeza, L. F., Rinc ón, L., Vilariño, V., Pérez, G., Castell, A.: Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review, Renewable and Sustainable Energy Reviews 29, 394-416 (2014).
3. Brambley, Michael R., Haves, Philip, M., Sean C, Torcellini, P., Hansen, D.G., Holmberg, D., Roth, K.: Advanced Sensors and Controls for Building Applications: Market Assessment and Potential R&D Pathways. United States: N. p., 2005.
4. Indian Real Estate Industry. Available from: https://www.ibef.org/industry/real-estate-india.aspx, Last Accessed: July 18, 2020.
5. Kumar, A., Hancke, G. P.: An energy-efficient smart comfort sensing system based on the IEEE 1451 standard for green buildings. IEEE Sensors Journal 14(12), 4245-4252 (2014).
6. Ahuja, V., Yang, J., Shankar, R.: Study of ICT adoption for building project management in the Indian construction industry. Automation in construction 18(4), 415-423 (2009).
7. Riggins, F. J., & Wamba, S. F.: Research directions on the adoption, usage, and impact of the internet of things through the use of big data analytics. In: 48th Hawaii International Conference on System Sciences, 2015, pp. 1531-1540, IEEE.
8. Atzori, L., Iera, A., Morabito, G. Social internet of things: turning smart objects into social objects to boost the IoT. Newsletter (2014). Available from: https://iot.ieee.org/newsletter/november-2014/social-internet-of-things-turning-smart-objects-into-social-objects-to-boost-the-iot.html. Last Accessed: July 18, 2020.
9. Sterman, John. Business Dynamics, System Thinking and Modeling for a Complex World. Irwin/McGraw-Hill, 2000
10. Forrester, J.W.: System dynamics, systems thinking, and soft OR. Syst Dyn Rev 10(2-3), 245-256 (1994).
11. Fisher, D. K., Norvell, J., Sonka, S., Nelson, M. J.: Understanding technology adoption through system dynamics modeling: implications for agribusiness management. The International Food and Agribusiness Management Review 3(3), 281-296 (2000).
12. AlWaer, H., D. J. Clements-Croome.: Key Performance Indicators (KPIs) and Priority Settings in Using the Mutli-Attribute Approach for Assessing Sustainable Intelligent Buildings. Building and Environment 45 (4), 799–807 (2010).
13. T.D.J. Clements-Croome, What do we mean by intelligent buildings? Automation in Construction 6, 395–399 (1997).
14. Ghaffarianhoseini, A., Berardi, U., AlWaer, H., Chang, S., Halawa, E., Ghaffarianhoseini, A., & Clements-Croome, D.: What is an intelligent building? Analysis of recent interpretations from an international perspective. Architectural Science Review 59(5), 338-357 (2016).
15. Kintner-Meyer, M.: Opportunities of wireless sensors and controls for building operation. Energy engineering, 102(5), 27-48 (2005).
16. Minoli, D., Sohraby, K., Occhiogrosso, B.: IoT considerations, requirements, and architectures for smart buildings—Energy optimization and next-generation building management systems. IEEE Internet of Things Journal 4(1), 269-283 (2017).
17. Bajer, M. IoT for smart buildings-long awaited revolution or lean evolution. In: IEEE 6th International Conference on Future Internet of Things and Cloud (FiCloud) 2018, 154, pp. 149-154, IEEE.

18. De Marco, A., Cagliano, A. C., Nervo, M. L., Rafele, C.: Using System Dynamics to assess the impact of RFID technology on retail operations. International journal of production economics 135(1), 333-344 (2012).
19. Qian, Y., Fang, Y., Gonzalez, J. J.: Managing information security risks during new technology adoption. Computers & security, 31(8), 859-869 (2012).
20. Mutingi, M. Understanding the dynamics of the adoption of renewable energy technologies: A system dynamics approach. Decision Science Letters 2(2), 109-118 (2013).
21. Kelic, A.: Networking technology adoption: System dynamics modeling of fiber-to-the-home. Doctoral dissertation, Massachusetts Institute of Technology, (2005).
22. Jia, M., Komeily, A., Wang, Y., & Srinivasan, R. S.: Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications. Automation in Construction 101, 111-126 (2019).
23. Jalali, M. S., Kaiser, J. P., Siegel, M., & Madnick, S.: The Internet of Things Promises New Benefits and Risks: A Systematic Analysis of Adoption Dynamics of IoT Products. IEEE Security & Privacy 17(2), 39-48 (2019).
24. Tripathi, S.: System Dynamics perspective for Adoption of Internet of Things: A Conceptual Framework. In: 2019 10th International Conference on Computing, Communication and Networking Technologies (ICCCNT), 2019, pp. 1-10. IEEE.
25. ASHARE Standard, ANSI/ASHRAE Standard 55. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers. Inc., Atlanta (1992).
26. Wang, H., Zhai, Z. J. Advances in building simulation and computational techniques: a review between 1987 and 2014. Energy and Buildings 128, 319-335 (2016).
27. Schwartz, Y., Raslan, R.: Variations in results of building energy simulation tools, and their impact on BREEAM and LEED ratings: A case study. Energy and Buildings 62, 350-359 (2013).
28. Brachman A.: Raport obserwatorium ICT. Internet przedmiotów, Technopark Gliwice, 2013.
29. Lilis, G., Conus, G., Asadi, N., Kayal, M.: Towards the next generation of intelligent building: An assessment study of current automation and future IoT based systems with a proposal for transitional design. Sustainable cities and society 28, 473-481 (2017).
30. Rafiq, N.R., Mohammed, S. F., Pandey, J., Singh, A.V.: Classic from the outside, smart from the inside: The era of smart buildings, In: 6th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO), Noida, 2017, pp. 580-584.
31. Moreno-Cano M.V., Santa J., Zamora-Izquierdo M.A., Skarmeta A.F. (2015) Future Human-Centric Smart Environments. In: Xhafa F., Barolli L., Barolli A., Papajorgji P. (eds) Modeling and Processing for Next-Generation Big-Data Technologies. Modeling and Optimization in Science and Technologies, vol 4. Springer, Cham
32. Klein, L., Kwak, J., Kavulya, G., Jazizadeh, F., Becerik-Gerber, B., Varakantham, P., Tambe, M. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. Automation in Construction 22, 525–536 (2012).
33. Hsinchun, C., Chiang, R.H.L., Storey,V.C.: Business Intelligence and Analytics: From Big Data to Big Impact, MIS Quarterly 36(4), 1165-1188 (2012).
34. Knutsen J.: Uprooting products of the networked city. International Journal of Design 8(1), 127-142 (2014).
35. Wan, T., Karimi, Y., Stanaćević, M., Salman, E.: Perspective paper—Can AC computing be an alternative for wirelessly powered IoT devices? IEEE Embedded Systems Letters 9(1), 13-16 (2017).

36. Ramesh, T., Ravi Prakash, Shukla, K. K.: Life cycle energy analysis of buildings: An overview. Energy and buildings 42.10 (2010): 1592-1600.
37. Zanella, A., Bui, N., Castellani, A., Vangelista, L., Zorzi, M.: Internet of things for smart cities. IEEE Internet of Things journal 1(1), 22-32 (2014).
38. Ma, Z., Badi, A., Jorgensen, B. N.: Market opportunities and barriers for smart buildings. In: 2016 IEEE Green Energy and Systems Conference (IGSEC), 2016, pp. 1-6, IEEE.
39. Hsu, C. W., Yeh, C. C.: Understanding the factors affecting the adoption of the Internet of Things. Technology Analysis & Strategic Management, 29(9), 1089-1102 (2017).