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Original Article

Analytical Hierarchical Process (AHP) as a decision-making model for retrofitting ordinary buildings into smart buildings

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Abstract

The last decades witnessed a rapid digital transformation showing how smart technologies and computational design are rapidly changing buildings, cities, and communities. Transformation of ordinary existing non-smart buildings into smart or semi-smart ones is important, to ensure enhancing the performance of buildings in the structure of smart cities. The presented study aims to identify a model for retrofitting existing ordinary buildings to become smart. The research focuses on smart buildings dimensions and indicators to be applied to existing buildings to make them more intelligent and smarter to be integrated into the smart city context. The research methodology encompasses three parts: a critical literature review for dimensions of smart buildings. Then an analytical approach illustrating case studies for smart retrofitted buildings. In addition to a descriptive-analytical approach that proposes a decision-making model based on Analytical Hierarchical Process (AHP) for retrofitting ordinary buildings into smart ones. Results point out the viability of such transformation in coping with the digital era and identify the necessities in turning ordinary buildings into smart ones to enhance sustainability for cities and communities.

1. INTRODUCTION

The sustained escalating development and applications of new disruptive technologies, digitized media, and computational design is altering the current practices in architecture and urbanism. The presented study focuses on transforming ordinary existing buildings into smart buildings, which will help contemporary cities in their smart digital transformation[1]. This could be achieved by retrofitting existing ordinary buildings with a smart and digital infrastructure that can enhance their sustainability in addition to increasing their efficiency. The study addresses the problem regarding the lack of significant strategies for transforming ordinary buildings into smart ones.

Thus, the research aims to identify a model for retrofitting existing ordinary buildings to become smart. Accordingly, this will help decision-makers in identifying optimum smart interventions and techniques in smart retrofitting for ordinary buildings. Thus, the research answers two main questions – how existing ordinary buildings could be retrofitted into smart ones while achieving the highest performance? –How smart buildings' indicators could change existing ordinary buildings to become smart and guarantee their sustainability?–.

2. LITERATURE REVIEW

The presented study starts with a systematic literature review that ends with a proposed decision-making model for helping decision-makers in transforming ordinary buildings into smart buildings.

2.1. Literature review data collection

This study targets selected publications in the Web of Science database for specific coverage of topics. The initial search was performed from September 2021 to November 2021. It used the formula: ("Transforming" AND "Ordinary Buildings" OR "Traditional buildings" AND "Smart Buildings", which helped in narrowing down the research to fit with the research's main objective. As a result, 419 publications were recorded representing journal articles, conference proceedings, books, and book chapters. This was considered reliable to build on literature data analysis for the transformation into smart buildings. Moreover, all selected articles were published from 2017 to 2021.

2.2. Literature review data analysis

Bibliometric analysis was performed using VOS software. Figure 1 shows the different keywords according to their co-occurrence in the selected articles. According to the performed analysis research on smart buildings transformation can be categorized into four main groups, namely; (1) buildings, (2) smart and sustainable applications, (3) automation and communication, and (4) management systems.

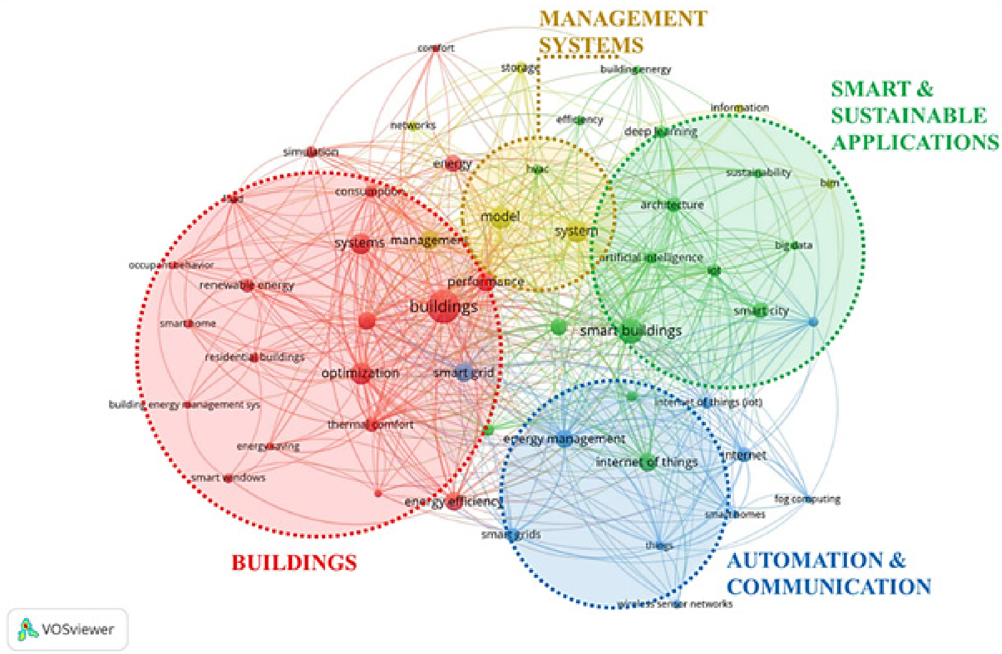

Fig. 1: Literature bibliometric analysis using VOS software (author).

2.3. Smart cities, smart buildings, and ordinary buildings (non-smart)

The idea of smart cities encompasses integrating Information Communication Technologies (ICT) with cities' structures[2]. Smart cities are based on six pillars namely; smart governance, smart economy, smart mobility, smart living, smart environment, and smart people[3]. According to the rapid development of technology smart cities evolves rapidly. It started with basic ICT applications, and now it depends on IoT (the internet of things). IoT mainly helps in the optimization of resource usage and increases the qualities of the presented services. IoT serves in lots of disciplines regarding smart cities like; network architecture, waste management, cyber security, energy management …etc. Thus it helps a lot in designing smart buildings as well as transforming buildings and cities to become smart[4]. "Smart buildings" and "intelligent buildings" are terms used to describe buildings that encompass new technologies with automated controls, smart networks of sensors, and data analytics software including efficient information systems and energy organization[5]. These networks allow the building itself to communicate with the other smart buildings in its surrounding context. On the contrary, buildings are known to be "ordinary" or "non-smart" when they are identified to have no specific structures or systems that include technological interventions in them[6]. Meanwhile, there are "Semi-smart" buildings,which are buildings with partial integration of smart, intelligent, and automated systems that are selected according to their suitability to the structure and capacity of the building itself[7].

2.4. Benefits and challenges of smart retrofitting of ordinary buildings

The main benefits of the transformation of old buildings into new ones are; energy reduction and resource optimization, and the enhancement of its safety and security. Operating maintenance and digital automated management systems, enhancing life cycle costs and better utilization of spaces, reducing risks, and saving money[6,7]. Moreover, smart retrofitting of buildings encompasses many challenges namely; the cost of acquisition which includes costs of installations, systems, and devices in addition to training the users of these buildings to manage and use the system itself. Cybersecurity and securing the data of the building itself to guarantee its sustainability[8], and lack of awareness, understanding the integration of systems and planning time. Also, lack of documentation for the building itself, old functioning systems and structures, and outdated data systems[9].

2.5. Examples for smart retrofitted buildings

Retrofitting is adding new elements and constituents to a building for making it perform better. However, it is known that working from scratch on creating smart buildings is much easier than updating an existing building[10]. Therefore, this section presents initiatives for smart retrofitting of old buildings, especially residential ones.To identify major interventions in existing structures and to show how this process works.

2.5.1. Soviet-era apartment buildings retrofitting, Tartu, Estonia.

The project covered the area of the city center of Tartu, Estonia as a pilot area for the project. It embraces 43 residential buildings but the project targeted 22 buildings. The smart interventions used in this project targeted the buildings and their surrounding context[11]. The project targeted achieving sustainable usersbehavior, zero energy levels, and enhanced quality of life. It followed the EU Directive 2010/31/EU Energy Performance of Buildings[12]. Accordingly, 12 specified actions were established namely; installing smart home systems, installing smart meters, installing video intercom buzzers at the doors, building electrical systems, installing solar panels, renovating the systems of ventilation, renovating the systems of hot water, renovating the heating systems, roof insulation, outer walls insulation, repositioning windows, enhancing exterior design[13]. Figure 2 explains the different actions for the retrofitting strategy.

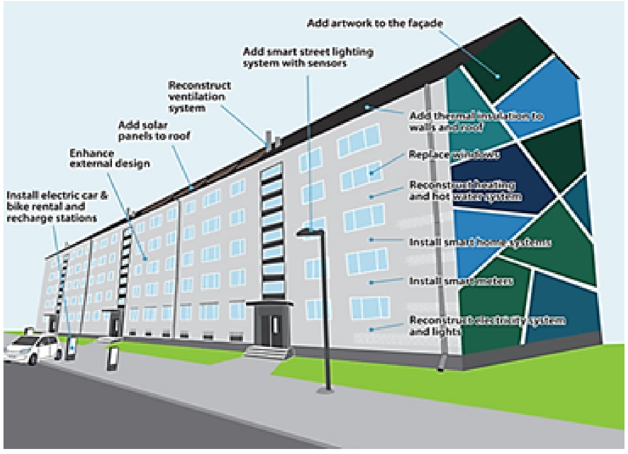

Fig. 2: The retrofitting actions[13].(Credit: Rein Ahas, Veronika Mooses, Pilleriine Kamenjuk and Raimond Tamm).

2.5.2. Spanish residential building, Bellpuig-La Vall, Spain.

Two attached blocks were built in 2009 in Spain. It is one of many projects held by 4RinEU who provides large-scale renovation projects for existing buildings to become smart[14], as shown in Figure 3 and Figure 4. The main problems in this building were thermal comfort and energy reduction. Thus, smart technical systems were added, to control air handling units and PV panels. In addition to prefabricated elements, new openings, and foundations as complementary interventions in the buildings offering better insulation and load-bearing solutions. Moreover, experts used BIM assistance in the design and production process[15].

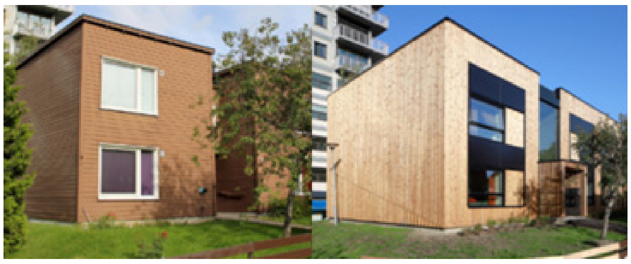

Fig. 3: "Before and after" illustration for the buildings[15] (Credit: Boligbygg and Ivan Brodey).

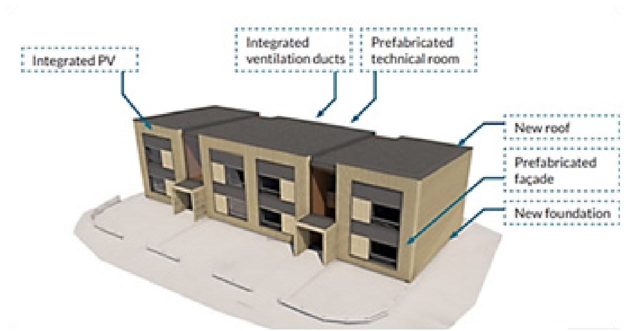

Fig. 4: The retrofitting interventions[15] (Credit: Filter Arkitekter).

3. METHODS AND PROCEDURES

The research study adopts a mixed-method approach. First, an inductive literature investigation, and then a descriptive-analytical approach to identify the indicators of smart transformation for buildings. The research ends with a decision model development based on Multi-Criteria Decision Making (MCDM) methods which were adopted in this study because it aims to provide a tool for decision-makers to retrofit existing ordinary buildings to become smart buildings. MCDM is very useful in achieving decisions and making choices that cannot be determined directly[16] it consists of various strategies that are used widely within the last decades, and it is applicable in several fields and specializations.

3.1. Selecting the most appropriate Multi Criteria Decision Making (MCDM) method

There are various MCDM methods that decision-makers can select from[17]. Different related methods to the objective of the presented study were reviewed such as; Multi-Attribute Utility Theory (MAUT), Analytic Hierarchical Process (AHP), Fuzzy Set Theory, and Case-based reasoning (CBR). All mentioned methods are applied in relevant areas like engineering, management, and planning. AHP was selected for this study since it is easy to use and has a scalable hierarchical structure, besides it can easily adjust to fit many problems. Developing the AHP model starts by identifying the decision problem and making sure it can be solved using AHP, then structuring the problem itself. Then identifying the raters (decision-makers) who will be involved in the process. They are only allowed to judge, rate, and make decisions. Then determining relative priorities of the different criteria and calculating its relative weight using pairwise comparison and Saaty scale shown in Figure 5.

1	Equal Importance	Equal contribution to the objective
2	Weak or Slight	
3	Moderate Importance	Slightly favor one activity over the other
4	Strong importance	
5	Strong importance	Strongly Slightly favor one activity over the other
6	Strong plus	
7	Very strong or demonstrated importance	An activity favored very strongly over another, its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	One activity favored over the other in highest possible order of affirmation
Reciprocals of above		If activity -i- has one of the above non zero numbers assigned to when compared with activity –j- then –j- has a reciprocal value when compared with –i-
1.1 – 1.9	Activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable. Yet they can still indicate the relative importance of activities.

Fig 5: Saaty fundamental scale for pairwise comparison[18] (presented by author).

To start developing the AHP model; it is important to review some terms and definitions first to understand its mathematical structure. Pairwise Comparison: It is a method for comparing attributes with each other to form a basis of design decisions and to decide the priority of each entity[16,17]. Consistency Ratio (C.R. Value): It is the ratio between the consistency of a given evaluation matrix and the consistency of a random matrix. Eigenvector (E.V.): It is a non-zero vector of linear transformation whose direction does not change when that linear transformation is applied to it[19].

3.2. Developing a hierarchical decision model

The hierarchical model for the decision problem needs to be formulated through four major levels, namely; Goal level; which is the topmost level where the decision problem is identified. Objectives level; are derived from the main four categories resulting from the bibliometric analysis. Criteria level; is presented in the indicators that help achieve each one of the previous objectives. Alternatives level; Alternatives are options that are targeted to be evaluated based on their attributes[19]. The model design aims to find out the best method for retrofitting an existing building to become a smart one giving optimum performance, accordingly the alternatives to be included in such a model are the different types of smart buildings regarding their functions.

3.3. Computing relative weigh

First, identify the problem and the case to work out the data needed. Then structuring the choice hierarchy by putting the goals of the decision the highest. Then comes the objectives from a broad perspective. Then the intermediate level is delineated within the criteria on that consequent parts depend. After that set of alternatives within the lowest level is introduced. Formerly assembling a set of pairwise comparison matrices, in which each element in an upper level is used to compare the elements in the level immediately below concerning it[20]. Consequently, using the priorities that are calculated from the previous comparisons to weigh the priorities in the below level. This should be performed for each element at all levels. Add its weighted values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom-most level are obtained[21].

4. RESULTS AND DISCUSSION

Based on the previous assessment a decision model based on AHP method was constructed illustrating the main contribution for this study, in which the research questions were addressed – how existing ordinary buildings could be retrofitted into smart ones while achieving the highest performance? – How does transforming existing ordinary buildings into smart ones guarantee their sustainability? – Figure 6 shows the decision-making model using AHP method.

The model mainly encompasses four sets of objectives including 15 indicators. The objectives are; (1) Smart management (SM); which is essential for energy saving, maintenance management systems, and emergency control. It is seen in light controls using sensors and louvers which are controlling sunlight inside the building, or natural ventilation and air conditioning controls. It is witnessed in emergencies like building evacuation during disasters like fire and activating smoke controllers during such emergencies, all this through the internet connection, which enhances safety and security inside the building. (2) Energy efficiency (EE); which can be adjusted by optimizing the energy required for the support functions of a data center, which is a system that encompasses all of the tools needed to enable building automation information technology. (3) Building automation (BA); which can improve different systems of the building itself by modifying start/stop times for occupied periods, maintaining a specified building environment, turning off/on lighting based on occupancy, and monitoring system performance. It achieves automatic control of inner-building equipment using sensors to collect data, which may then be forwarded to the equipment's intelligent signal acquisition for completely automatic control. It includes a central administrative station, controller, and sensors that perform a variety of network system control and management functions. Sensors, actuators, controllers, buses, and other interfaces are all part of this system. (4) Smart communication (SC), which is mainly concerned with inner communication (inner system), and outer communication which depends on intelligent network infrastructure. It serves the main idea of smart buildings as a part of smart grids which can easily communicate with their surrounding context. 15 indicators are set in the criteria level.

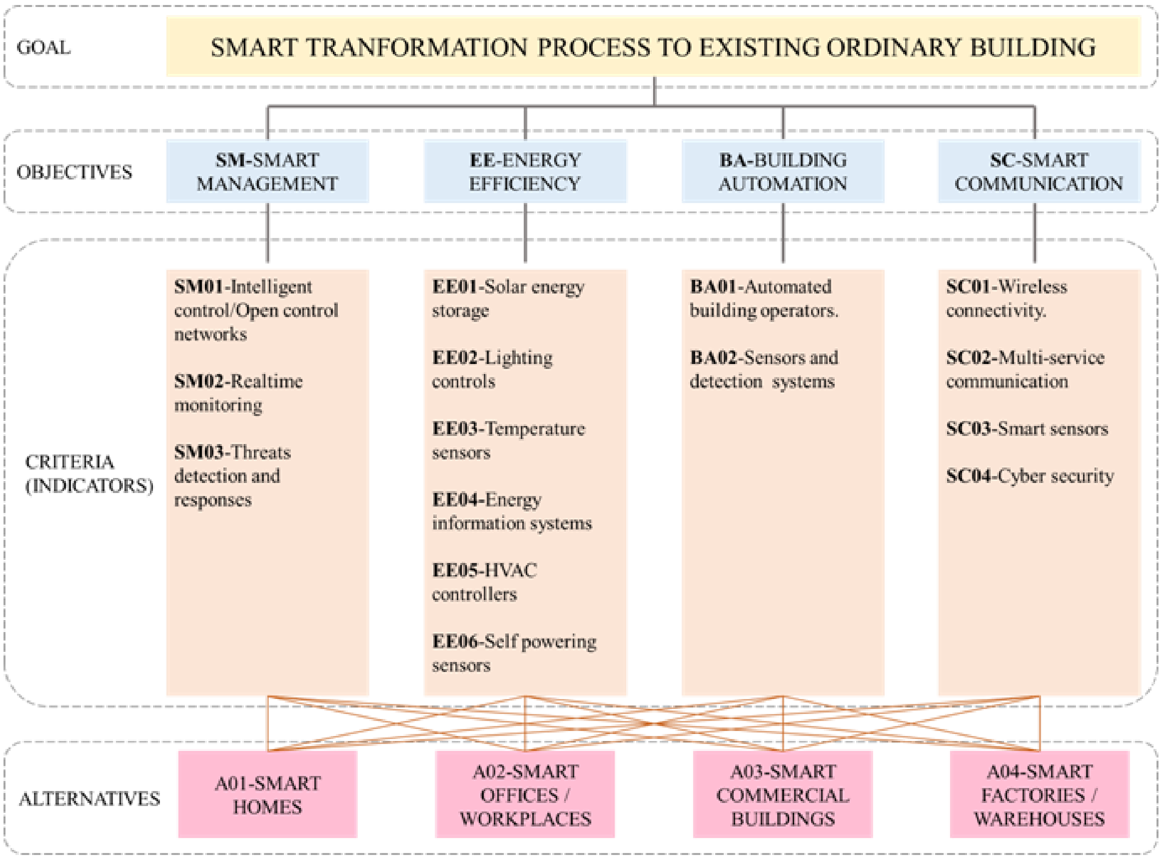

Fig. 6: AHP decision making model for smart retrofitting of ordinary buildings (author).

Each set of indicators has inner connections with other sets of indicators; Moreover, each indicator has an outer connection with others from the four sets. These connections are translated in the model as a pairwise comparison process between all the objectives and indicators together using the Saaty scale. Meanwhile, alternatives are introduced to the model to adjust the process selection for retrofitting buildings to become smart, they are set to be pair-wisely compared to each other to complete the proposed model performance. Then the introduced alternatives are smart homes (A01), smart offices or workplaces (A02), smart commercial buildings (A03), smart factories or warehouses (A04). According to the selected decision modeling process, the alternatives are to be pair-wise compared with the indicators. Then a relative weight will be calculated indicating the priorities of each alternative. This comparison will be represented in a decision matrix where each alternative is compared to the other in the form of a pairwise comparison concerning each one of the indicators. A decision matrix is the final form of the proposed decision AHP model elaboration[18]. It is a matrix that represents the relation between the selected four alternatives of the model and the 15 indicators assigned to measure it[19]. In other words, if the alternatives are K and the indicators are L the decision matrix is defined as KxL matrix, in which element xij represents the value of the i-th alternative on the j-th attribute[20]. Figure 7 shows the establishment of the model's decision matrix connecting the indicators and the alternatives to choose from. The results calculated from this matrix are referred to as local priorities that are calculated with relation to the considerations. Then the local priorities in addition to the relative weight of the considerations; are used to calculate the overall priorities for the alternatives using the following equation:

Overall priority = ∑ local priority with respect to indicators X criteria weight (1)[21]

OBJECTIVES	INDICATORS		ALTERNATIVES			
			A01-SMART HOMES	A02-SMART OFFICES/WORK PLACES	A03-SMART COMMERCIAL BUILDINGS	A04-SMART FACTORIES /WAREHOUSES
SMART MANAGEMENT (SM)	SM01	Intelligent control/Open control networks				
	SM02	Real-time monitoring				
	SM03	Threats detection and responses				
ENERGY EFFICIENCY (EE)	EE01	Solar energy storage				
	EE02	Lighting controls				
	EE03	Temperature sensors				
	EE04	Energy information systems				
	EE05	HVAC controllers				
	EE06	Self powering sensors				
BUILDING AUTOMATION (BA)	BA01	Automated building operators.				
	BA02	Sensors and detection systems				
SMART COMMUNICATION (SC)	SC01	Wireless connectivity.				
	SC02	Multi-service communication				
	SC03	Smart sensors				
	SC04	Cyber security				

LOCAL PRIORITIES FINAL WEIGHT (E.V.)

Fig. 7: Decision matrix for the alternatives and the indicators (author).

5. CONCLUSION

The presented study identified the likely criteria and indicators that needed to be taken into consideration to transform an existing ordinary building into a smart building. The research study adopted Analytical Hierarchical Process (AHP) as one of the Multi-Criteria Decision Making (MCDM) methods. AHP is beneficial to achieve the research main objective -identifying a model for retrofitting existing ordinary buildings to become smart ones-. This will help decision-makers to identify optimum smart interventions and techniques in smart retrofitting for ordinary buildings - The research pointed out the main directives for retrofitting an existing building to become smart namely; automation, smart and sustainable applications, energy efficiency, and smart communication. Regarding the study limitations; literature review bibliometric analysis showed that there are important gaps in this field of research. It identified four groups resembling dimensions for smart retrofitting. But these groups are not covered in a balanced manner. Findings and conclusions point out suggestions for future research namely; empirical investigation through adding a case study and using focus groups of decision-makers for the proposed AHP model to check the process as a whole. Also, it will show different weights and priorities which will support the model formulation.

6. REFERENCES

[1] J. Vuolteenaho, K. Leurs, and J. Sumiala, "Digital urbanisms : Exploring the spectacular , ordinary and contested facets of the media city," Obs. J., vol. 2015, pp. 1–21, 2015, doi: https://doi.org/10.15847/obsOBS002015970.

[2] N. S. N. Wahab, T. W. Seow, I. S. M. Radzuan, and S. Mohamed, "A Systematic Literature Review on The Dimensions of Smart Cities," IOP Conf. Ser. Earth Environ. Sci., vol. 498, no. 1, p. 12087, 2020, doi: 10.1088/1755-1315/498/1/012087.

[3] S. Tarek and A. S. E.-D. Ouf, "Biophilic smart cities: the role of nature and technology in enhancing urban resilience," J. Eng. Appl. Sci., vol. 68, no. 1, p. 40, 2021, doi: 10.1186/s44147-021-00042-8.

[4] K. Szum, "IoT-based smart cities: a bibliometric analysis and literature review," Eng. Manag. Prod. Serv., vol. 13, no. 2, pp. 115–136, 2021, doi:10.2478/emj-2021-0017.

[5] A. Mahmoud and A. Elkhiary, "Simulation Analysis for evaluating Smart technique of Energy Performance in Egypt," 2019, doi: 10.1088/1755-1315/397/1/012002.

[6] R. Panchalingam and K. C. Chan, "A state-of-the-art review on artificial intelligence for Smart Buildings," Intell. Build. Int., pp. 1–24, 2019, https://doi.org/10.1080/17508975.2019.1613219.

[7] E. I. Batov, "The Distinctive Features of 'Smart' Buildings," Procedia Eng., vol. 111, pp. 103–107, 2015, doi: https://doi.org/10.1016/j.proeng.2015.07.061.

[8] C. Panteli, A. Kylili, and P. A. Fokaides, "Building information modelling applications in smart buildings: From design to commissioning and beyond A critical review," J. Clean. Prod., vol. 265, p. 121766, 2020, doi: https://doi.org/10.1016/j.jclepro.2020.121766.

[9] D. Minoli, K. Sohraby, and B. Occhiogrosso, "IoT Considerations, Requirements, and Architectures for Smart Buildings—Energy Optimization and Next-Generation Building Management Systems," IEEE Internet Things J., vol. 4, no. 1, pp. 269–283, 2017, doi: 10.1109/JIOT.2017.2647881.

[10] W. Knowles, D. Prince, D. Hutchison, J. F. P. Disso, and K. Jones, "A survey of cyber security management in industrial control systems," Int. J. Crit. Infrastruct. Prot., vol. 9, pp. 52–80, 2015.

[11] M. Manic, D. Wijayasekara, K. Amarasinghe, and J. J. Rodriguez-Andina, "Building Energy Management Systems: The Age of Intelligent and Adaptive Buildings," IEEE Ind. Electron. Mag., vol. 10, no. 1, pp. 25–39, 2016, doi: 10.1109/MIE.2015.2513749.

[12] J. King and C. Perry, Smart buildings: Using smart technology to save energy in existing buildings. Amercian Council for an Energy-Efficient Economy, 2017.

[13] R. Ahas, V. Mooses, P. Kamenjuk, and R. Tamm, "Retrofitting Soviet-Era Apartment Buildings with 'Smart City' Features: The H2020 SmartEnCity Project in Tartu, Estonia BT - Housing Estates in the Baltic Countries: The Legacy of Central Planning in Estonia, Latvia and Lithuania," D. B. Hess and T. Tammaru, Eds. Cham: Springer International Publishing, 2019, pp. 357–375.

[14] D. Matskevits, "Energy efficient Renovation Strategies: Estonia and European Sustainability Project," 2020.

[15] 4RinEU, "Robust and Reliable technology concepts and business models for triggering deep Renovation and residential Buildings in the EU," 2020. [Online]. Available: https://4rineu.eu/wp-content/uploads/2021/06/4RinEU-booklet-Renovate-deep-and-renovate-fast.pdf?utm_source=web&utm_medium=download&utm_campaign=booklet.

[16] G. K. L. Lee and E. H. W. Chan, "The Analytic Hierarchy Process (AHP) Approach for Assessment of Urban Renewal Proposals," Soc. Indic. Res., vol. 89, no. 1, pp. 155–168, 2008, doi: 10.1007/s11205-007-9228-x.

[17] J. Bragge, P. Korhonen, H. Wallenius, and J. Wallenius, "Bibliometric Analysis of Multiple Criteria Decision Making/Multiattribute Utility Theory BT - Multiple Criteria Decision Making for Sustainable Energy and Transportation Systems," 2010, pp. 259–268.

[18] T. L. S. Katz, "Decision making with the analytic hierarchy process," Int. J. Serv. Sci., vol. 1, no. 1, pp. 83–98, 2008, doi: 10.1108/JMTM-03-2014-0020.

[19] D. L. Xu and J. B. Yang, "Introduction to Multi-Criteria Decision Making and the Evidential Reasoning Approach.," 2001. [Online]. Available: https://www.researchgate.net/publication/228602548_Introduction_to_multi-criteria_decision_making_and_the_evidential_reasoning_approach.

[20] T. L. Saaty, "The Analytic Hierarchy Process: Decision Making in Complex Environments BT - Quantitative Assessment in Arms Control: Mathematical Modeling and Simulation in the Analysis of Arms Control Problems," R. Avenhaus and R. K. Huber, Eds. Boston, MA: Springer US, 1984, pp. 285–308.

[21] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, and J.-H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making," Renew. Sustain. Energy Rev., vol. 13, no. 9, pp. 2263–2278, 2009, doi: https://doi.org/10.1016/j.rser.2009.06.021.