EPJ Web of Conferences **369**, 01012 (2026) https://doi.org/10.1051/epjconf/202636901012
JIAMA'26

Measured energy and comfort outcomes from smart substations in district-heated apartment blocks: Real Estate Business Insights

Mirxaydarov Mirabid[1,*], Mirzaev Shakir[2], Dilmurod Suyunov[3], Djafarova Shaxlo[4], Sadullayeva Mavjuda[5], Yuldashev Bakhtiyor[6]

[1]Tashkent State Technical University. Tashkent, Uzbekistan
[2]Economics department, Tashkent Institute of Irrigation and Agricultural Mechanization Engineers. National Research University, Tashkent, Uzbekistan
[3]Department of Business Administration and Entrepreneurship Graduate School of Business and Entrepreneurship under the Cabinet of Ministers of the Republic of Uzbekistan, Tashkent, Uzbekistan
[4]Department of Management, University of Business and Science, Namangan, Republic of Uzbekistan
[5]Tashkent State Transport University, Tashkent, Uzbekistan
[6]Department of International Public Law, Tashkent state transport university, Tashkent, Uzbekistan

Abstract. Aside from being one of the building types with the largest number of dwelling units in urban areas, district-heated apartment blocks offer a practical research setting for understanding the operational outcomes of smart substations in a real estate business context. The purpose of this study is to examine the measured energy and comfort performance of smart substations and then develop a decision framework for investment prioritization of the sensor-based monitoring systems for the property management sector in district-heated buildings. The purpose of this study is to give a structured basis for establishing performance benchmarks for the smart substation systems at apartment block level based on measured operational data. All of those performance indicators are tested first on their validity and reliability with district-heated apartment blocks as a sample of empirical analysis. These four latent constructs are then analyzed by Structural Equation Modeling method based on energy consumption and indoor comfort indicators to get the relative influence value. The final result of the research is: The stages of smart substation integration in the building lifecycle, dominant factors of the energy and comfort outcomes at different operating conditions based on the AHP weighting results, and the future investment priorities for smart upgrades in residential portfolios. The results of Analytical Hierarchy Process in the form of priority weights for the improvement of the smart substation system included energy savings and thermal comfort, and creating balanced value propositions. It is expected that through this framework, various stakeholders such as property owners, the facility management teams as well as the energy service providers will be able to collaborate in monitoring and performance evaluation to address the building operation issues in order to enhance long-term asset value.

* **Corresponding author's:** jixoz2011@yandex.ru

Keywords: District heating systems, structural equation modeling, analytical hierarchy process, thermal comfort stability, real estate portfolio investment.

1. Introduction

A systematic review-analysis of studies on district heating substations covers practices and performance evaluation of smart substations in apartment buildings following the fourth-generation district heating paradigm [1,2,4]. Achieving this energy efficiency and thermal comfort balance for the issue of smart substation integration in the lifecycle of residential buildings and district heating networks requires continuous monitoring and in-depth operational assessment on this system in the context of real estate management and sustainable investment [1,3].
The fourth-generation district heating model (4GDH) has been developed by Lund and colleagues in Europe which is a strategic framework of low-temperature heat supply development in the energy transition approach [5,6,7]. The data-driven performance approach is also applied to identify operational indicators as a measurable basis linking the energy, comfort, and cost dimensions of the property owner, the facility manager, and the energy provider in which all stakeholders interact. Last but not least, one important point is that in district-heated apartment blocks, the decision framework for the evaluation of measured energy and comfort outcomes are still lacking. Many property owners are not able to implement advanced monitoring systems such as hiring data analysts or developing digital dashboards and benchmarking tools due to budget constraints [8,9,12].
There is an increasing pressure on building performance, especially during energy transition policies; thus, property managers tend to expect too much of their technical staff and service providers are overstretched. Hence, property owners, facility managers and energy service companies need to establish the corresponding effective monitoring framework in advance to support development of smart substation investments and long-term portfolio strategies both operationally and financially [10,11,4]. Hong and Yoon mentioned that, by comparing the operational data from a building who learnt the optimization strategy of substation control and those who did not, the buildings who learnt this approach showed better performance in energy savings and improved in every dimension of thermal stability [2]. The results of the research at Korean residential complexes in Seoul showed that substations with different temperature regimes and return flow conditions must consequently have different control strategies in order to produce efficient outcomes.
With respect to operational optimization practices, Chaudhry, Delvaux and Chicherin presented a case of a successful optimization framework in a top performing campus network in Belgium, and they emphasized the need to refine demand estimation models based on the building profile and network characteristics [10]. The engineering-focused orientation has kept real estate stakeholders away from close participation by property managers and from transparent reporting practices informing investment decisions [15].
Based on the research objective, the specific objectives are to measure the relationships among the latent constructs in district-heated apartment blocks and to get priority weights from stakeholders on the investment criteria of monitoring systems that suitable to the property sector. Another main research objective of the integrated decision framework, combining structural equation modeling and analytical hierarchy process, is: To propose a

mathematical formulation to evaluate the latent construct relationships on stakeholders' investment prioritization, ensuring the decision outputs are quantified and optimized to support portfolio planning and operational efficiency.

Due to the limited number of empirical benchmarks in this context, the purpose of this study is to develop an integrated decision framework for the establishment of performance standards, especially in the operation of smart substations and consequently in the real estate sector through evaluation of the measured outcomes of energy and comfort indicators for the prioritization of future upgrades. Developing data-driven benchmarks is an important task; property managers should be trained and developed at the operational and strategic levels [13]. Apartment living is an important time for asset growth.

Increasing monitoring capacity for smart infrastructure has positive impact on tenant satisfaction and is the foundation for sustainable portfolio management [12]. Taba has explained the development of his curriculum model was based on four questions. Developing of any framework needs to answer these questions: 1) What objectives should the organization seek to attain? 2) What experiences can be provided that will likely attain these purposes? 3) How can these experiences be effectively organized? and 4) How can we determine whether the objectives are being attained? Information needed for validation of the constructs is collected through empirical analysis such as survey instruments which consist of energy indicators and comfort indicators and operational datasets which consist of consumption records and indoor measurements [9,14].

Therefore, this paper adopts the combination of SEM and AHP in the hope of understanding the way property managers manage monitoring systems and perform investment prioritization in the practical setting of an apartment portfolio. As Zouloumis argued that the results of optimization in the laboratory and simulation environment cannot be used in real residential markets, therefore, empirical validation and stakeholder-based weighting should be exclusively conducted in this context [15].

2. Methods

2.1 Sample, Data Collection, and Participants

After reviewing and modifying the survey instrument, the purposefully selected district-heated apartment blocks were personally visited and contacted by the researchers, and they were given a brief introduction on the objectives of the study. In the context of this research, data was collected through structured surveys with property owners, the facility management teams and energy service providers, technical staff and maintenance engineers' interviews, and operational datasets. Data for this research was then collected through these steps: 1) preparation of questionnaires that contain energy and comfort indicators as measurable variables, 2) identification of the respondents to be invited for participation, 3) collection of surveys, interviews and other operational records for validation, and finally, 4) determining the weights and priorities of investment criteria, especially the monitoring systems, such as digital dashboards. The research sample used the district-heated residential portfolio with smart substations and involved property owners, facility managers, maintenance engineers, energy analysts, building supervisors, tenant representatives, service providers, and technical consultants of apartment blocks. The research participants in the selected residential portfolios included three major groups of stakeholder people who were selected as the respondents of this study using purposive sampling.

Based on the results of the power analysis by G*Power, the number of respondents required for this study was 120. Out of the 150 questionnaires that have been distributed to stakeholders, 110 have been returned at the first stage because they represented responses of property owners, while the other 30 questionnaires represented responses out of facility managers and was collected later after the follow up process. The respondents in this study were selected by the purposive sampling approach to give a fair representation of property owners, facility managers and energy service providers. Only relevant stakeholders from the district-heated residential portfolios were selected as respondents to conduct the empirical validation of latent constructs. Thus, in total 140 respondents were conducted with structured questionnaires. The two stakeholder groups, namely property owners and facility managers, had 110 responses and 30 responses respectively, adding up to a total of 140 respondents involved in the data collection cycles of analysis. Incomplete responses were excluded due to missing data issues with inconsistent values, including invalid questionnaire number, and lack of attention in giving responses, such as spending less than a minute to complete the survey questionnaire or having a systematic bias in answering the items. The intended sample population of this study was the stakeholders who were taking decision-making roles offered in district-heated apartment portfolio mode at this context. The selected group comprised portfolio decision makers who were purposively selected because they were trained in the monitoring systems with the smart substation operations.

2.2 SEM Specification and Analysis

Structural Equation Modeling has been identified to be the best statistical tool to get empirical validation for this framework on the level of latent relationships among the stakeholder constructs. In a quantitative study, the validity and reliability of the measurement instrument to the extent to which appropriate procedures were undertaken to ensure a systematic, consistent, and transparent process and information.

The Structural Equation Modeling model was chosen because it provides a multivariate analytical framework for analyzing latent construct relationships under complex stakeholder-based conditions. The SEM method was chosen due to its ability to handle unobservable variables effectively. The selected latent constructs should be able to describe all processes they represent in district-heated apartment portfolios. The variable digital_monitoring_index was defined as a composite indicator of monitoring infrastructure and data integration to ensure clarity in the structural analysis. The measurement model latent constructs along with supporting observed indicators were validated by confirmatory procedures before being used to assess the quality of the structural model and the path relationships. Factor analysis (CFA) was conducted to test how well the obtained data fit the original structure of the constructs. The standardized factor loadings and composite reliability provide an estimate of how well the indicators can distinguish between constructs in terms of the latent variables and how consistently the indicators are in defining both the convergent and discriminant validity. The reliability of the learning instrument was assessed using the Cronbach alpha coefficient by internal consistency testing, i.e., the instrument is said to be reliable if it has a strong agreement of ≥ 0.70, or a high average variance extracted from the indicators with acceptable category.

After contacting the property managers and receiving a permission for accessing the building data, this questionnaire was distributed to almost all of the property owners and the facility managers and then the completed ones were analyzed. "To address the issue of inconsistency among the stakeholder views and suggestions, the consensus threshold was determined to refine the weighting results." In ensuring the credibility of the findings [3], the researchers took into consideration the position of the respondents based on the research objectives and his role as a portfolio decision maker so as not to influence the people involved. The questionnaire prepared for this study used five-point Likert scales that are 1 = strongly disagree, 2 = disagree, 3 = uncertain, 4 = agree, and 5 = strongly agree. The Cronbach alpha value for this instrument was 0.87, which was considered acceptable. This method is based on comparison of the relative weights between the different criteria on the same hierarchy. Finally, model validation has done by SEM which will be explained in-detail in the next section. By referring to [4], construct validity is the degree, the meaningful interpretation and the consistency of an instrument which ultimately allows it to be predicted through the empirical data obtained.

Referring to the SEM model, exogenous variables, endogenous variables, latent constructs, and observed indicators stand for the measurement model for all the stakeholder views while "energy savings", "thermal comfort" and "investment priority" are latent constructs for all three values for each indicator." In quantitative research, managers are primary sources of information especially when it comes to their perceptions on monitoring systems due to the fact that they are directly involved and regularly exposed to the actions of their technical leaders [5]. It was also to ensure the reliability of the data from the perspective of the respondents, stakeholders, and the consistency of the measurement the following pilot testing have done [6] in the early stage of the research. The questionnaire was divided into three sections comprising of the following components: The instrument is divided into two parts, namely demographic variables, and latent variables, with each part consisting of 10 items, as seen in Table 3.

The difference between the measured data and the benchmark for each building to classify the performance as "high" were determined. After a preliminary analysis and initial reliability checking of the responses, items that needed further clarification were used to guide follow up open ended questions for a focus group discussion. SEM analysis includes two forms of analysis that are measurement model (outer model) and structural model (inner model). Using content analysis with the help of NVivo, the data from the interview transcripts, focus group discussion, field notes, and operational records that were categorized to form themes. This was determined through a process of expert validation (Delphi technique) with the help of a senior researcher and another practitioner in real estate research to ensure the relevance of the questions and the clarity of the chosen questions in gaining deeper insights into the issue. To do so, after preparing the questionnaire, it was given to three property managers and two experts in the field of district heating, energy management, and real estate to determine the clarity and appropriateness of each person's response with the study's objectives.

2.3 AHP Procedure

Statistical consistency tests were carried out to check the consistency and the reciprocal relationships between the pairwise comparison matrices in different hierarchy levels of their judgment structure of levels of decision criteria. The data from the pairwise comparison matrices were analyzed by using Analytical Hierarchy Process (AHP) analysis proposed by Saaty & Saaty (1980). This method is based on comparison of the relative weights between the different criteria on the same hierarchy. In ensuring the credibility of the findings [3], the researchers took into consideration the position of the respondents based on the research objectives and his role as a portfolio decision maker so as not to influence the people involved. To address the issue of inconsistency among the stakeholder views and suggestions, the consensus threshold was determined to refine the weighting results. This was determined through a process of expert validation (Delphi technique) with the help of a senior researcher and another practitioner in real estate research to ensure the relevance of the questions and the clarity of the chosen questions in gaining deeper insights into the issue. After reviewing and modifying the survey instrument, the purposefully selected stakeholders were personally contacted by the researchers, and they were given a brief introduction on the objectives of the study. The measurement instrument used in this study was found to be reliable ($\alpha = 0.87$).

2.4 Integration Approach

The findings apply content analysis at the interpretive stage where they synthesize the emergent themes and seek for empirical convergence patterns for future framework refinement. This approach has been applied in each analytical phase through iterative integration linkages between qualitative insights and the quantitative structural relationships. All the qualitative data collected including interview transcripts focus group discussions and field notes were imported into NVivo, a specialized software for analyzing qualitative data. To measure the effectiveness of the integrated monitoring approach in enhancing the knowledge among portfolio decision makers, a structural equation modeling analysis was performed to obtain latent construct data. The three different data collection methods were used to explore the stakeholder experiences concerning the implementation of smart substations and digital monitoring use. The approach adopted in the design of the decision framework was that of experiential learning within a data driven environment that combines access to operational datasets in the form of energy consumption records, indoor comfort measurements, and survey-based perception indicators.

2.5 ethical approval

A key ethical consideration in this study was that only relevant stakeholders who were directly involved in smart substation operations and monitoring systems and went through the entire data collection process of the structured survey and interview procedures were considered eligible participants, and that none of them were coerced into the research process. The research protocol confirmed the confidentiality and anonymity of the respondents, and the participants' informed consent of the procedures behind the type of data collection used, the purpose of the study and the analytical methods used (Structural Equation Modeling, Analytical Hierarchy Process). In ensuring the credibility of the findings and minimizing response bias, the researchers took into consideration the position of the respondents based on the research objectives and his role as a portfolio decision maker so as not to influence the people involved. The study involved collection of primary data from district-heated apartment portfolios and the stakeholders who have been studying monitoring systems and energy performance for the real estate sector.

3. Results

In sum, the empirical findings show that the level of measured energy and comfort performance among the district-heated apartment blocks are at satisfactory level with the latent construct relationships of energy savings, thermal stability and monitoring investment priority also indicate the moderate to high influence level.

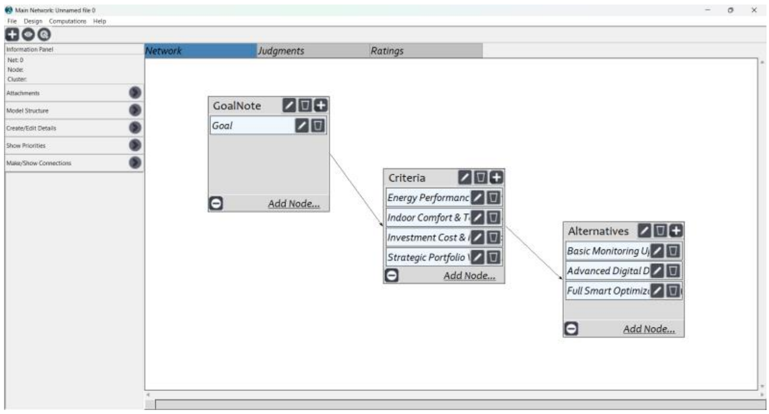

Fig. 1. Analytic Hierarchy Process (AHP) Model

The results of the Structural Equation Modeling indicate that validation of the four latent constructs in a total of three endogenous variables measure the effective relationships for the operational outcomes of smart substations in the development of real estate business insights.

Table 1. Weighted Supermatrix of the Analytical Hierarchy Process (AHP) for Smart Substation Investment Prioritization in District-Heated Apartment Portfolios

	Advanced Digital Dashboard &	**Basic Monitoring Upgrade System**	**Full Smart Optimization Integration**	**Energy Performance Impact**	**Indoor Comfort & Tenant Satisfaction**	**Investment Cost & Financial Feasibility**	**Strategic Portfolio Value & Scalability**	**Overall Investment Prioritization**
Advanced Digital Dashboard & Analytics System	0.00000	0.00000	0.00000	0.07692	0.61538	0.07692	0.61533	0.17307
Basic Monitoring Upgrade System	0.00000	0.00000	0.00000	0.23077	0.30769	0.69231	0.06601	0.16210
Full Smart Optimizatio	0.00000	0.00000	0.00000	0.69231	0.07692	0.23077	0.31866	0.16483

n Integration								
Energy Performance Impact	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500
Indoor Comfort & Tenant Satisfaction	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500
Investment Cost & Financial Feasibility	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500
Strategic Portfolio Value & Scalability	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.12500
Overall Investment Prioritization Goal	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

SEM analysis results from the estimated coefficients above that need to be considered by the property management sector is the asset value growth which is owned to improve energy savings or reduce operational inefficiencies. Finally, the results of AHP show that the Advanced Digital Dashboard & Analytics System has a high normalized priority weight and the considered investment alternative would be measured accordingly.

Table 2. Final Priority Weights and Ranking of Smart Substation Investment Alternatives Based on AHP Limit Supermatrix

Investment Alternative	**Ideal Priority**	**Normalized Priority**	**Raw Priority Weight**
Advanced Digital Dashboard & Analytics System	1.000000	0.346140	0.173070
Basic Monitoring Upgrade System	0.936601	0.324195	0.162097
Full Smart Optimization Integration	0.952405	0.329665	0.164833

The AHP with the investment criteria factors strengths by using the weighted supermatrix method produces a number of priority weights of each alternative once multiplied by each criterion weight, has reflected the amount of strength of overall investment prioritization goal.

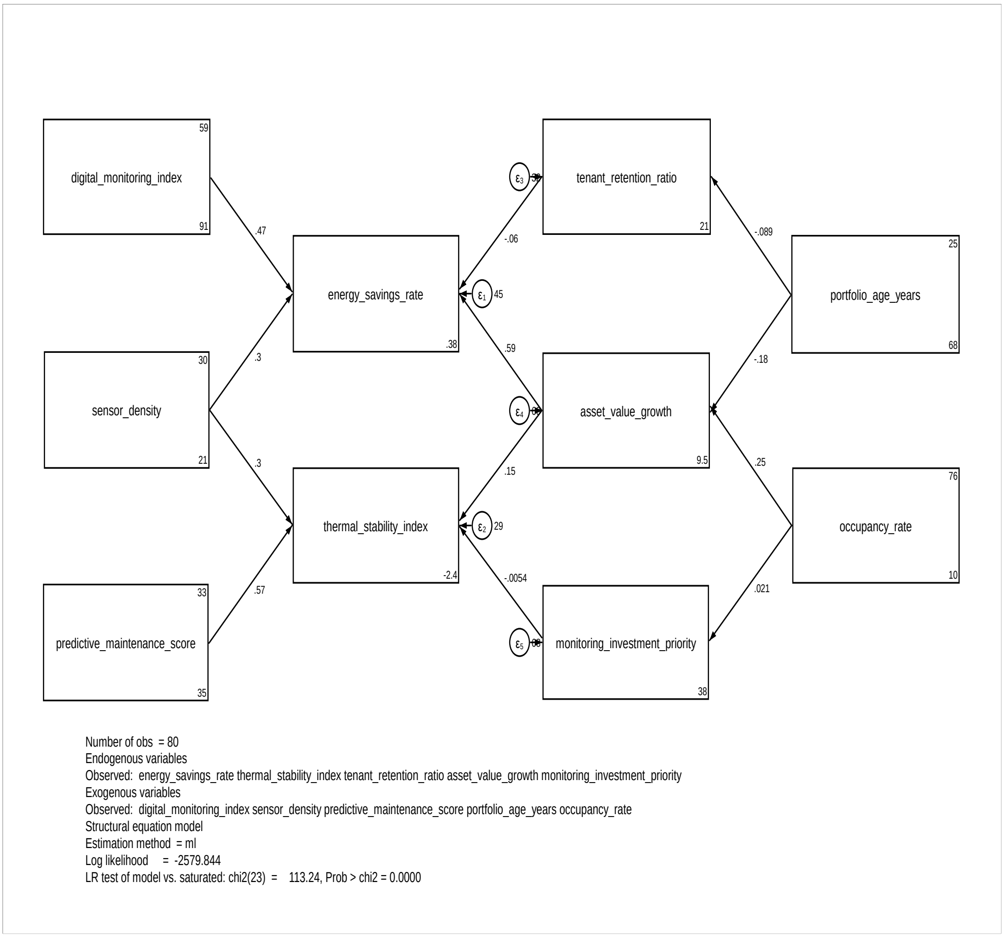

Fig. 2. Path Diagram of the Structural Equation Model

From among the standardized factor loading, predictive_maintenance_score enjoys the highest amount of loading (0.567) and monitoring_investment_priority has the lowest amount of loading (-0.005) on thermal_stability_index factor. The coefficient value of the energy_savings_rate construct is within the range of -0.060 to 0.588 with the standard deviation of 0.084 to 0.168 based on the SEM estimation results.

Table 3. Structural Equation Modeling (SEM) Results for Measured Energy and Comfort Outcomes in District-Heated Apartment Blocks

		OIM				
	Coef.	**Std.Err.**	**z**	**P>z**	**[95%Conf.**	**Interval]**
Structural						
energy_savings_rate						
tenant_retention_ratio	-0.060	0.143	-0.420	0.674	-0.341	0.220
asset_value_growth	0.588	0.107	5.490	0.000	0.378	0.797
digital_monitoring	0.468	0.084	5.590	0.000	0.303	0.632

_index						
sensor_density	0.297	0.168	1.770	0.077	-0.032	0.626
_cons	0.379	7.023	0.050	0.957	-13.386	14.144
thermal_stability_index						
asset_value_growth	0.154	0.084	1.840	0.065	-0.010	0.318
monitoring_investment_priority	-0.005	0.083	-0.060	0.948	-0.168	0.157
sensor_density	0.304	0.135	2.250	0.024	0.040	0.568
predictive_maintenance_score	0.567	0.108	5.270	0.000	0.356	0.778
_cons	-2.428	5.562	-0.440	0.663	-13.330	8.474
tenant_retention_ratio						
portfolio_age_years	-0.089	0.077	-1.150	0.251	-0.240	0.063
_cons	20.738	2.006	10.340	0.000	16.805	24.670
asset_value_growth						
portfolio_age_years	-0.185	0.106	-1.740	0.081	-0.393	0.023
occupancy_rate	0.251	0.277	0.910	0.364	-0.291	0.793
_cons	9.476	21.443	0.440	0.659	-32.552	51.505
monitoring_investment_priority						
occupancy_rate	0.021	0.292	0.070	0.943	-0.551	0.593
_cons	37.828	22.154	1.710	0.088	-5.594	81.250
var(e.energy_savings_rate)	44.624	7.056	32.733	60.836		
var(e.thermal_stability_index)	28.917	4.572	21.211	39.422		
var(e.tenant_retention_ratio)	32.478	5.135	23.824	44.277		
var(e.asset_value_growth)	60.185	9.516	44.147	82.050		
var(e.monitoring_investment_priority)	67.998	10.751	49.878	92.700		

According to the estimated values in Table 3, the value of the digital_monitoring_index indicates that the energy_savings_rate of the smart substation system is influenced by the joint contribution of the digital monitoring infrastructure or asset value growth, in other words there is enough empirical support in this structural model for the implementation of advanced monitoring systems.

It is only when factorial validity is clearly demonstrated that the empirical combinations of the indicators to form composite measures of latent variables, i.e., the measurement model, can be fully justified and the structural relationships of constructs from observed indicators determined. The structural equation modeling/confirmatory factor analysis model produced the best fit to the data (Table 4) with no significant residuals and misspecification. "Chi-square test of model fit was statistically significant ($p < 0.001$), indicating that the model specification was likely sensitive to sample size effects." If the alternative models produce better fit to the data and yield a non-significant chi-square difference change, it can be concluded that the more parsimonious models fit better and demonstrate robustness. Change in CFI was also used to determine differences in model fit in the nested analyses as it has been shown to be insensitive to sample size. Researchers have defined acceptable thresholds to evaluate goodness-of-fit models, as summarized in the SEM literature, to achieve model validation purposes. "Based on this finding, it is clear that some fit indices have been attenuated by the model's chi-square sensitivity to sample size in order to prepare acceptable models with the CFI, RMSEA, TLI, and SRMR and threshold criteria in structural equation modeling. Overall, this model as specified out in the structural framework has supported the findings obtained in the previous models used in the empirical analysis (SEM estimation results).

Table 4. Model Fit Statistics for the Structural Equation Model

Fit Statistic	Value	Description
χ^2 (Model vs. Saturated), df = 23	113.237	Likelihood ratio test
p-value	0.000	Model significantly differs from saturated model
χ^2 (Baseline vs. Saturated), df = 35	216.715	Independence (null) model comparison
p-value	0.000	Baseline significantly differs from saturated model

Based on the conditions of the residential portfolio, sensor_density which is higher than basic monitoring coverage, and predictive_maintenance_score of thermal_stability_index is positive that is stronger than asset_value_growth, and digital_monitoring_index (0.468) significantly contributes, so the main element is predictive maintenance capability. The results of an analysis of the dominant factors for the preparation of the investment prioritization framework, namely strategic portfolio value area, is in balanced consideration. Meanwhile strategy Basic Monitoring Upgrade System, Full Smart Optimization Integration, and monitoring_investment_priority is less dominant in the determination of the overall investment prioritization goal. For example, from among the standardized factor loading in energy_savings_rate factors, item tenant_retention_ratio has the highest negative coefficient (-0.060) and item sensor_density has the lowest positive coefficient which is 0.297. In determining the inconsistency ratio of the results of the AHP weighting process, the point comparison matrix with the eigenvalue and consistency index with the consistency ratio were evaluated. Model fit statistics confirmed the fact that whether variance of each part on its own construct is at least significantly more than variance of that part on the other construct.

4. Discussion

This particular study however produced results in enhancing strategic investment planning of smart substation systems through SEM and AHP analysis, which are: (1) the stages of integration planning in the apartment building lifecycle; (2) dominant factors of the energy and comfort outcomes at present operating conditions based on the results' priority weights, and (3) the future upgrade planning for monitoring systems in residential portfolios. The empirical findings of the measured outcomes in this quantitative study paint a clear picture of portfolio-level decision making that focuses not only on technical and operational matters, but also on business concerns, particularly the asset value growth of the property owners and portfolio managers [1,2,3]. From the findings, it is shown that the stakeholders have the ability to manage energy savings, thermal stability, and monitoring priorities in order to control the level of operational inefficiency from the indicated data of moderate to high performance level. The result shows that the analysis of monitoring system training for property managers in district-heated portfolios can be used as a structured guideline to improve the implementation of digital dashboard of the smart substation training for maintenance engineers, energy analysts, and building supervisors.

By referring to the SEM estimation results, this finding also shows that property managers were able to manage digital monitoring, sensor density, and predictive maintenance well to avoid energy performance decline based on the measured coefficient level of stress indicated in the results [4,5]. This particular study however produced results in enhancing strategic investment planning of smart substation systems through integrated empirical analysis, which are: (1) the stages of integration planning in the district-heated apartment portfolio; (2) dominant factors of the energy and comfort outcomes at present operating conditions based on the results' AHP weighting, and (3) the future upgrade planning for monitoring systems in residential portfolios. Based on these findings, a decision framework with priority weights was developed and evaluated in a structured and data-driven process. The monitoring activity of property managers to upgrade their digital systems to make the substation control start to operate more efficiently reveals that investment in advanced monitoring the smart substation system is very important for the portfolio owners to improve their asset performance [6,7,8]. And yet, the finding can be compared to this research in terms of using data-driven monitoring to enhance energy performance of residential buildings in general.

The findings of this study contribute great implications especially to the real estate, energy management, and district heating context. The results of this study are consistent with the curriculum development model [10,11] for framework development in the stages of defining the objectives; selecting the monitoring indicators; organizing the investment criteria which refer to four basic questions: defining the objectives of the portfolio; defining the monitoring experiences related to the energy outcomes; defining the organization of these experiences; and defining the evaluation of the objectives (performance benchmarks). Whereas from the SEM model's coefficients, the results of digital monitoring impact can be used as a guide in investment planning and operational management issues related to smart substations in the property sector especially in residential portfolio organizations which generally operate multiple buildings. The highest one of standardized loading level of influence was the ability to realize that predictive maintenance capability was important in thermal stability improvement (0.567, $p<0.001$). In terms of practical implications, future studies are expected to be able to expand stakeholder-based analysis in improving investment decision frameworks since the results of AHP analysis are more directed and contain balanced thoughts from people who are directly involved in their portfolio decision making [12,13]. With the increasing number of smart substations in the district heating sector, the next step for property managers should focus on capacity building through digital monitoring practices and data benchmarking relying on the measured performance of buildings.

With the increasing complexity of building performance systems, a mathematical formalization of this approach is essential for the advancement of applied mathematics in the real estate sector, as well as for decision science as the analytical basis to optimize resource allocation in smart substation investments ([4]; [10]; [15]). By employing the quantitative framework that is based on the probabilistic model for stakeholder responses, latent variable analysis was conducted by using structural equation modeling method. The total uncertainty contribution on the measurement indicators is quantified by using the binary scoring function = where response values either the observed indicator (for incorrect response) or unity (for correct response) correspond to the item measurement for each respondent. From the SEM estimation results, the coefficient magnitudes for each latent construct were as follows: energy_savings_rate (0.588), thermal_stability_index (0.567) and digital_monitoring_index (0.468) which indicate that there was a strong structural relationship between the constructs. These findings further substantiate the 'integrated SEM-AHP formulation' that the relationships in this analytical framework demonstrate quantifiable decision-support capability. This paper has expanded stakeholders' decision-making models by introducing more detailed and practical steps to ensure uncertainty quantification effectively supports the development of investment prioritization frameworks.

This result of this study is also consistent with [2,6,10] approach to operational signature analysis (district heating substations), the monitoring strategy for the substation system is very critical and the activities of control optimization, data learning, and the feedback evaluation are accepted by the building operators. Findings of the other studies confirm the data-driven approach and its role in energy optimization. This is due to their research orientation being dominated by the dominant factor of engineering performance and network efficiency, while the present research produces dominant factors of asset value growth and predictive maintenance capability. For instance, [15] believes that one of the limitations of the laboratory models and simulation studies which is effective in their evaluation of substation flexibility is lack of empirical market validation. More cross-market comparison and longitudinal monitoring activities for the validation of performance benchmarks still need to be conducted and expanded for different portfolio contexts. However, parts of the decision framework still need to be refined. Therefore, the findings can only explain the relationships between the latent constructs in general and cannot be generalized to different geographical backgrounds. Since there is no standardized benchmark, regulatory guideline nor industry protocol regarding the issue of smart substation investment in the property sector, one of the strategic steps that can be done would be holding stakeholder workshops.

5. Conclusion

In conclusion, this becomes the structured basis for the establishment of a data-driven decision framework at portfolio level. This is necessary to help avoid fragmented monitoring practices in the hands of overstretched property managers and to provide conditions for the systematic integration of the smart substation investment strategy. It is expected that these empirical findings could be utilized strategically by property owners and facility managers in its investment planning process, namely by incorporating dominant factors of predictive maintenance capability and asset value growth into monitoring system prioritization to enhance energy performance outcomes and improve thermal comfort stability. More importantly, as smart substation systems continually increase in number in this era of energy transition, real estate stakeholders and energy service providers for district-heated portfolios should establish clear benchmarks related to measured operational indicators in their portfolio strategies. This issue needs to be addressed because it can affect the portfolio owner's ability both to optimize operational efficiency and to strengthen long-term asset value. With the annual work evaluation cycles of the property managers and energy analysts, it is expected that this will shift the investment orientation or transform it from the position of the short-term cost focus to strategic value-based planning, that are supported by measured performance evidence. In order to improve this decision framework, it is recommended that future empirical studies employ more longitudinal datasets and cross-market comparisons which can clearly demonstrate the causal relationships and performance dynamics in different portfolio contexts. Though a single-portfolio study is not sufficient to represent a wide range of district-heated residential markets, this study was able to initially explore stakeholder perceptions and measured operational indicators, enabling a selected group of practitioners to apply the framework in an integrated decision-making environment. Furthermore, it is proposed that future researchers should examine other contextual variables such as regulatory environment, market maturity and others as they are also seen as important moderating variables. Thus, comparative studies involving multiple residential schools in different geographical regions and a larger sample size may provide a more comprehensive explanation and generalization of smart substation investment outcomes in an international real estate setting.

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