Data Quality Assessment for Building Performance Analysis with Pilot Case Study

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Abstract

In the era of the Fourth Industrial Revolution, the utilization of IoT technologies has greatly simplified the process of acquiring building performance data. However, when it comes to analyzing building performance, especially in Energy Audits and Retro-commissioning (RCx), the issue of poor data quality persists. This poor data quality can result in misinterpretation of the situation, thus impeding the identification of decarbonization opportunities and potentially causing an increase in operating costs. This paper will delve into a comprehensive framework for assessing data quality, which consist of three assessment criteria – Critical (which will affect the accuracy of results of building performance analysis), Efficiency (which will affect the efficiency in analysis) and Optional. Each criterion has corresponding assessment characteristics and associated metrics. The framework has been tested in a pilot project with existing building management system in Hong Kong, which helped define and enhance data quality.

Key Word

Data Quality Assessment, Building Performance Analysis, Retro-Commissioning, Data Audit

1. Introduction

1.1. Background and Motivation

Building performance data plays a critical role in operations and energy management, allowing designers, facility managers and related personnel to gain insights to identifying areas for improvement in resource optimization, emission reduction, and cost cutbacks. Automatic real-time sensing devices provide close monitoring of building conditions. Retro-commissioning (RCx) of existing buildings heavily relies on data collected by these devices to identify energy poor-performers and fabricate strategies for equipment efficiency improvement without disrupting regular operations and occupants' comfort.

Under digital transformation of smart buildings, distributed sensing technology will continue to be heavily deployed in the near future. It suggests not only the significance of data quality, but also the consequence for the lack of it. Data quality needs to be "measured, controlled, and improved" [1], especially in the building sector, as high economic and environmental costs are often implied behind operational and maintenance (O&M) decisions. Data with poor quality leads to incorrect and ineffective decisions on equipment replacement schedules, potentially resulting in misjudgment in capital investments. It also impedes building decarbonization approaches by delaying early realizations of emission hot spots. Failing to take timely actions to meet building emission reduction targets heavily hinders the industry's progress towards net-zero. The lack of guidance for BMS data quality inhibits adherence to regulations, lowering abilities to mitigate risks and avoid penalties.

Preliminary research has been conducted to apprehend the current stage of development in safeguarding data quality. There are no existing standards for quality of building management system (BMS) data, leaving a gap of uncertainty in data interpretation. Most published research papers remain on the level of literature review. Against this background, a building-specific data quality framework is developed based on literature reviews of past studies and relevant standards. BMS data needs to bear certain qualities to allow correct interpretation of the receiver. The framework proposed in this study explains a list of universally applicable assessment criteria for BMS data quality. It addresses the research gap by introducing metrics to assess data quality for identifying potential unsatisfactory data sources, followed by category-specific recommendations for quality improvements.

1.2. Research Objective

This research aims at defining data quality measures for quantitatively measuring the data quality with reference to the international standards, in particular the ISO/IEC 25024: 2015 and ISO/IEC 25012:2008, which was developed for Systems and Software engineering.
To achieve the proposed framework, the following study objectives must be met:

- To critically review existing research on data quality in building energy management, and data quality standards of other sectors;
- To develop key performance indicators for BMS data quality, and map their relevance to RCx and other building operations and maintenance work;
- To apply the criteria in assessment of a local (Hong Kong) project's BMS database and make corresponding recommendation for improvements;
- To provide insights for application of framework in other building RCx projects and future research direction to create a standard in which the industry agrees upon.

2. Literature Review

To aid this study's framework development, other literature was reviewed to evaluate the current progress in BMS data quality management.

A paper on building data quality was published in 2023 (Morewood, J. et al.) (2023), reviewing 162 existing building monitoring studies where data quality was reported. [2]

The research highlighted the absence of comprehensive reporting about data quality, and how seldom such concepts are described in published articles, stating only "3.23 data quality concepts out of a total of 11 classified" reported in the articles on average [2]. The granularity of data is identified as a major issue, and reasons for that include varied accuracy of market available sensors and collection time interval. Fragmentation in data cleaning poses risks on quality, as the treatments for different parameters were not consistent. Data cleaning was also not widely adopted, as less than 30% of the reviewed studies included it. [2]

Limitations of the study include incomplete reporting, as published articles were often written in a concise manner. Detecting quality-related keywords might not be able to reflect reality, leading to inaccurate analysis. The paper, however, provides a relatively complete overview of current progress of building data quality, and insights for bettering data governance.

ISO 25024:2015, Systems and software Quality Requirements and Evaluation (SQuaRE), gives a fundamental list of data quality measurements that are integrated into a quality model for data. [3] This standard defines qualities that are taken into consideration when assessing information generated or collected by a software product. Upgraded from ISO 9126, it provides 15 measurement aspects and corresponding sub-elements for data quality analysis.

Gaps in current building data management are identified.

1. There is an absence of standardization and consensus on BMS data quality requirements. While there are international standards on data quality monitoring, the building sector lacks visibility in forming robust and consistent guidelines for the industry to follow. The increasing reliance on Artificial Intelligence (AI) to analyze data implies a need for higher quality and uniformity of data. [4]

2. Reporting of data quality is currently not a mandatory requirement. Building data transparency has often been avoided due to privacy and business considerations. Without quantified and comprehensive quality measurements, data governance is not effectively demonstrated. Benchmarking remains a challenge as it involves determining which data attributes are critical for comparison.

3. Lack of awareness for data quality prevails in the building sector. The aim of RCx is to evaluate the building equipment's performance by identifying areas for improvement to

achieve energy saving and cost reduction. Trusting BMS data of poor quality heavily impedes the success of RCx projects and results in capital misspend.

This study references the above two published pieces to formulate a framework for BMS data quality assessment. The framework is further applied to an on-going project in Hong Kong MTRC, where data is reviewed and evaluated under the proposed criteria.

3. Stakeholders

Different stakeholders' approaches to BMS data often vary based on the separate intentions of use. For instance, facility managers organize and look at data to ensure smooth building operations, whereas an RCx team uses the data for energy performance evaluation and efficiency improvements. Data quality directly influences their interpretations, analysis, and decision-making that would ultimately determine the overall building performance.

The table below summarizes stakeholders identified in ISO 25024:2015 who need to "use data quality measures while pursuing their responsibilities." [3] Stakeholders in the building sector are included to illustrate their individual relevance to data quality management.

- *Building Management System (BMS) Consultant* – is responsible for designing, installing, and managing the control systems catering to the building's functions and occupants' needs.

- *Facility Manager (FM)* - is responsible for O&M of building services to support smooth running and legal compliance to building and environmental standards.

- *Mechanical, Electrical, Plumbing (MEP) Consultant* – is responsible for planning and designing building systems catering to the building's functions and occupants' needs.

- *RCx Team* – is responsible for planning, implementing, and reporting of a periodical check on an existing building's performance to identify operational improvements for energy and cost saving.

- *Energy Auditor* – is responsible for reviewing energy consuming equipment or systems in a building to formulate strategies for Energy Management Opportunities (EMO).

- *Sustainability Consultant* - is responsible for advising on sustainability strategies including a building's energy efficiency and carbon emissions.

- *Data Specialist* – is responsible for monitoring and improving raw databases to translate data into understandable formats for other stakeholders' use.

- *Property Owners* – is responsible for contracting a team of the above experts to ensure an adequate level of building performance and legal compliances.

Stakeholder	**Definition**	**Stakeholders in the Built Environment**							
		BMS Consultant	*Facility Manager*	*MEP Consultant*	*RCx Team*	*Energy Auditor*	*Sustainability Consultant*	*Data Specialist*	*Property Owner*
Acquirer	An individual or organization that acquires or procures data from a supplier		✓		✓	✓		✓	
Evaluator	An individual or organization that performs an evaluation, which can, for example, be a testing laboratory, the quality department of an organization, a government organization, or a user		✓		✓	✓	✓	✓	
Developer	An individual or organization that performs development activities including requirements, analysis, design, implementation, and testing data during the data-life-cycle	✓		✓					
Maintainer	An individual or organization that performs operation and maintenance activities of data	✓	✓					✓	
Supplier	An individual or organization that enters into a contract with the acquirer for the supply of data or service under the terms of the contract	✓							
User	An individual or organization that uses data to perform a specific function		✓		✓	✓	✓	✓	✓
Quality Manager	An individual or organization that performs a systematic examination of the data		✓		✓		✓	✓	
Owner	An individual or organization that takes responsibility for the management and financial value of the data with the legal authority and responsibility to establish for them evaluation, collections, access, dissemination, storage, security, and cancellation		✓						✓

Figure 1 - Stakeholders using or managing BMS data

4. Framework

The proposed framework aims to consolidate new BMS design, as well as to improve the existing BMS to achieve data quality. It serves as a reference for future energy audit and/or RCx works, which helps identify issues in BMS system design and adopt appropriate data cleansing techniques and assumptions to carry out required analysis in an efficient and effective way.

The building sector is subject to an emerging series of assessments and audits based on energy, carbon, and efficiency standards. This framework promotes better understanding of operational performances in this increasingly stringent condition. It provides aid for the industry-players to smoothly transition their practices to embrace this trend and seize opportunities to upgrade their assets in a data-driven manner.

With reference to the international standards on data quality (ISO 25024:2015) [3] and understanding on building performance analysis (e.g. ASHRAE 211 [5], Technical Guidelines on Retro-commissioning issued by Electrical and Mechanical Services Department [6]).

The data quality framework which will be presented in the next section contains the following:

- Proposed characteristics;
- Set of data quality measures for each proposed characteristic;

Each measure has the own assessment metrics. The metrics would be revealed in the range from zero to one, where one represented the best performance in particular measure and / or characteristics.

The overall framework is presented as follows:

Criteria	Characteristic	Measures
Critical	Measurement Certainty	Outliers
		Trueness
		Sensor Accuracy
		Resolution
	Completeness	Attribute Completeness
		Data Retrival Ratio
		Record Completeness
	Consistency	Data Format Consistency
		System Consistency
	Granularity	Temporal Granularity
		Spatial Granularity
Efficiency	Processing Efficiency	Data Processing Efficiency
	Understandability	Metadata and data value Understandability
Optional	Credibility	Credibility
	Currentness	Currentness
	Accessibility	Accessibility
	Compliance	Compliance
	Confidentiality	Confidentiality
	Traceability	Traceability
	Availability	Availability
	Portability	Portability

Figure 2 - Proposed Data Quality Framework for BMS

Characteristics are categorized into the following: Critical Criteria, Efficiency Criteria and Optional Criteria. Critical Criteria directly affects the analysis result or the credibility of building performance analysis. Efficiency criteria refers to characteristics without direct impacts on the analysis result but determines the efficiency in data analysis and data processing techniques. Optional criteria include characteristics without impact on the building performance analysis but are good practice to ensure system reliability in software engineering point of view.

4.1. Critical Criteria

4.1.1. Measurement Certainty

Measurement certainty reveals ensure the ability to reveal true value by the measurement figures. It could be achieved by proper design and maintenance.

It is contributed by the following measures:

1) Outliers

Outliers refer to values that are significantly different from the other values in numerical terms. It could be determined by different methods, such as normal distribution and quantiles. It can be determined by the data range, if values fall outside theoretical range, it will be regarded as outliers as well. For example, a temperature sensor could only operate from 0℃ and 40 ℃, for values fall outside the range could be considered as outliers. There is no 'the best' solution for parameters, which should depend on the nature of parameter, such as the distribution of values and its skewness.

2) Trueness

Trueness pertains to the extent to which the sensors accurately indicate the true measurement value. The assessment of trueness depends on the calibration procedure specific to each sensor. Calibration should be conducted at regular intervals as advised by the manufacturers. The installation would influence the measurement result as well. For example, certain amount of straight pipe shall be reserved before flow meters to minimize flow distortions.

3) Sensor Accuracy

The higher of the sensor accuracy ensures the higher ability of the sensor capturing the true value. Different type of meters may refer to different standards on meter accuracy, for example, power meter could refer to BS EN 60521[7], flow meters could refer to ISO 4064 [8].

4) Resolution

Precision measures provide the degree to which data has attributes that are exact or that provide discrimination in a specific context of use. It could be revealed by the parameters' resolution. The required resolution of a particular sensor shall refer to specific standards. If no specific requirement, a general rule of thumb could be used to determine the required resolution by using number of decimal places / digits the design value multiplied by the design condition value with round function. For example, the design chilled water supply and return temperature were assumed to be 7℃ and 12.5℃ respectively. 1 % of the design condition would be 0.07℃ and 0.125 ℃ respectively. By rounding the figure, the required resolution would 0.1℃ for both parameters.

4.1.2. Completeness

Completeness refers to "the degree to which data associated with a target entity has expected values for all related properties of target entity in a specific context of use." (ISO 25024:2015).

It is contributed by the following measures:

1) Attribute Completeness

Attribute completeness is demonstrated by datasets including sufficient parameters for analysis of desired level of depth. In the RCx context, data from all attributes suggested by technical guidelines, for instance chilled water flowrate, should be collected and logged. The applicability of parameters in data collection is highly dependent on building provisions and equipment configurations. Technical guidelines also vary according to the location of publication.

Equipment No.	Location	Installed Capacity (Ton)	Chilled Water Temp. (°C) Supply Return		Flow Rate (L/s)	Evaporator Pressure (kPa)	Condenser Pressure (kPa)	Rated Power (kW)	Brand	Model No.	Type of Drive (e.g.CSD/VSD)

Figure 3 Example of attributes required in central chiller plant system (Reference from HKSAR EMSD Technical Guidelines on Retro-commissioning)

Attribute completeness does not limit to building level but can be equipment specific. An example would be chilled water pump including parameters of temperature, pressure, and flowrate, whereas condenser water pump only includes flowrate. This incompleteness in data collection may lead to misalignment and misrepresentation of the actual operational performance, as equipment with similar provision should adopt a list of shared parameters.

2) Data Retrieval Ratio

Data retrieval ratio refers to the ratio of data items that could successfully retrieve from the system for analysis to the data items available to be collected in the data management system such as building management system.

3) Record Completeness

Record Completeness is demonstrated by the extensive presence of records in datasets. There should be sufficient samples of datapoints for analysis. Missing data contributes against completeness, as loss of information often reduces the correctness of interpretation.

4.1.3. Consistency

1) Data format consistency

Data format consistency refers to the uniformity and standardization of data within a system. It ensures that data is structured and organized in a universally understandable format. Correct definition of data type is also essential for analysis. Data consistency facilitates efficient data management and integration. Building service equipment often belongs to a complex system. Uniformed and systematic naming and grouping enhance validity in data analysis, as it reduces redundancy and possible interpretation errors, especially in automated reporting.

2) System Consistency

System Consistency refers to the standardization of data format within a system. For example, given chilled water temperature was measured in two chillers. The naming of the two sensing parameters shall be the same.

4.1.4. Granularity

Data granularity is essential and determines the type of analysis that could be conducted as well as the level of details.

1) Temporal Granularity

It refers to the time interval that sensors update the information. From international and local guidelines (e.g. ASHRAE Guideline 14 [9], and HKSAR EMSD Technical Guidelines on Retro-commissioning [6]), it is recommended to have measurement interval of 15 minutes. 30-60 mins could be acceptable. The temporal granularity would affect the ability of data set revealing the operation pattern, and hence correlation with other exogenous factors, such as occupancy.

2) Spatial Granularity

It refers to the density of sensors to be implemented. It is divided into different levels: facility level, system level and equipment level. Facility level refers to measuring the performance of entire facility, for example, the power meter that measures the total power consumption of the whole building. The system level refers to meters that measures performance of specific service system, for instance, the power meter that measures the chiller plant consumption, the temperature sensors that measures supply and return temperature of chilled water in main header. The equipment level refers to meters that only measures performance of specific equipment.

It is recommended for major equipment, such as chillers, cooling tower and pumps could have equipment level measurement, because the condition monitoring could be critical in building performance analysis, while other equipment such as luminaires could have system level measurement to ensure sufficient spatial granularity for performance analysis.

4.2. Efficiency Criteria

Efficiency criteria define the metrics that have no direct implications on the analysis results, however, it would influence the working time and efficiency on the data analysis.

4.2.1. Processing Efficiency

Building management system has to store varies data, proper management on data input could reduce storage space and enhance efficiency in data retrieval. There are two data logging mechanisms, namely: event logging and interval logging. Event logging enables the system to capture data when the reading of sensor has changed, while the interval logging will capture data from sensor at a certain time interval regardless changes in the reading. The logging mechanism shall be determined based on the nature of data (e.g. frequency in updating reading, whether it is analog or digital signal). Using correct data logging mechanisms could reduce storage space.

4.2.2. Understandability

Understandability measures provide the degree to which data has attributes that enable it to be read and interpreted by users, and are expressed in appropriate languages, symbols and units to be used (ISO 25024).

1) Metadata and Data Value Understandability

Abbreviations are widely used in the industry, such as ‘WCC’ is referring to water-cooled chiller. However, some of the abbreviations may have different meanings in different contexts, such as ‘CH’ could refer to chiller, but it could also interpret as ‘chilled water’. Therefore, clear specifications could help others understand the context. Moreover, it is also important to state the unit of measurement.

4.3. Optional Criteria

With reference to ISO 25024:2015, the proposed framework identified 8 optional criteria that can potentially contribute to data quality improvements but may not be applicable or quantified in the building context. They include:

- Credibility
- Currentness
- Accessibility
- Compliance
- Confidentiality
- Traceability
- Availability
- Portability

Four of the above have higher relevance and application to the built environment, and therefore, are discussed in this paper.

4.3.1. Currentness

Instant feedback of signals of sensory device is critical in system control. Therefore, real-time reporting of data is prioritized for the best representation of reality, especially for trend identification. Delay of data transmission should be kept within acceptable range and constantly monitored. Currentness also measures the frequency of system updates needed.

4.3.2. Compliance

Compliance reflects the data's adherence to regulations and standards. In building management, it can refer to legal compliance with building regulations or operational specifications, or meeting audit requirements for various building standards, like LEED or RESET certifications [10]. Specific guidelines, such as required resolutions for sensors and time intervals for data collection, should not be overlooked if data compliance is wished to be achieved.

4.3.3. Confidentiality

Data confidentiality can be essential to organizations, especially when data is considered as sensitive information. This criterion measures the strength of protecting confidential data from unauthorized access, disclosure, or alteration. It can be achieved by encrypting data, restricting access privileges, and implementing security protocols. Under typical conditions, BMS data should only be made available to stakeholders contracted by property owners to carry out respective responsibilities contributing to the improvement of building performance.

4.3.4. Availability

Building data should be accessible and ready for use by relevant personnel whenever needed. All data should be properly stored and easily retrieved for no less than 36 months to demonstrate adequate availability. [6] Data backup, system update, or any other process that may disable data access should be shortened. A good level of data availability promotes work flexibility and the smooth-running of building systems.

5. Data quality assessment

Each measure in each characteristic would share the same weight. Therefore, to assess the performance of a specific characteristic, and hence criterion, could be done by obtaining average value.

5.1. Assessment on a specific characteristic

$$X_{ch} = \frac{1}{n}\sum_{i=1}^{n} X_{m,i}$$

Where:

X_{ch} is the overall performance of specific characteristic (Range 0-1, 1 means the best)

n is the number of measures in particular characteristic

$X_{m,i}$ is the rating of i^{th} measure

5.2. Overall performance in particular criteria

$$X_{Cr} = \frac{1}{n}\sum_{i=1}^{n} X_{ch,i}$$

Where:

X_{Cr} is the overall performance of specific criteria (Range 0-1, 1 means the best)

n is the number of characteristics in specific criteria

$X_{ch,i}$ is the rating of i^{th} characteristic

5.3. Interpretation of metrics

The metrics of each measure, characteristic and criteria were designed from range of zero to one. The performance could be interpreted with the following rating:

Rating	Range of Metric
Excellent	≥ 0.8
Good	0.5 ≤ X ≤ 0.8
Fair	< 0.5

Figure 4 Interpretation of Metrics

6. Case Study

Figure 5 - Elements by MTR Corporation Limited

6.1. Overview

Elements is a project developed by MTR Corporation Limited. Located on top of Kowloon Station with direct train to Hong Kong International Airport and right next to International Commerce Centre (the tallest building in Hong Kong), it is a 4-storey shopping mall with a total internal floor area of 179,010 square meters. RCx for the building kickstarted in December 2022 and is expected to conclude around May 2025.

MTR Corporation has long been one of the leaders embracing digital transformation in Hong Kong and agreed to incorporate the proposed framework of data quality into the RCx process of Elements. A list of relevant data quality measurement criteria was chosen and applied to analyze BMS data collected. Results can be observed below:

Criteria	Sub-Category	Result
Measurement Certainty	Outliers	Excellent
	Trueness	Fair
	Accuracy	Fair
	Resolution	Excellent
Completeness		Fair
Consistency	System Consistency	Fair
	Data Format Consistency	Fair
Granularity	Temporal Granularity	Fair
	Spatial Granularity	Good
Credibility/Data Provenance	Data Source	Excellent
Currentness	Real-time	Excellent
Uniqueness		Excellent

Figure 6 - Data Quality Assessment Result of the Elements

6.2. Project Implications

This is one of the world's very first applications of data quality evaluation framework in building performance. This case study acts as proof for practicality of the proposed framework. Using the specified criteria for data quality assessment of an existing project ensures the measurement considerations are logical and applicable specifically to building management system. The evaluation also sheds light on the alignment of data quality concepts with existing RCx and other auditing standards. It also discloses potential compliance challenges with such standards and identifies areas of improvements for the framework. Data experts can acquire data processing techniques when understanding the real-life application of previously abstract concepts, so that they are more equipped to put together data quality management strategies.

This case study is particularly important in BMS design and considerations, as the evaluation pinpoints potential risks of data quality fallacies existing in current designs. It also provides insights on BMS's integration with digitization trends for building management, such as artificial intelligence and chiller plant optimization, in turn raising the industry's awareness on the important of data quality and smart building development.

7. Discussion

The table below summarizes the factors affecting the proposed criteria.

Proposed Criteria		Measures	*Uncontrollable*	*Controllable*	
			Condition-related	**Equipment-related**	**Formating-related**
Critical	Measurement Certainty	Outliers	✓	✓	
		Trueness	✓	✓	
		Sensor Accuracy		✓	
		Resolution		✓	
	Completeness	Attribute Completeness	✓	✓	✓
		Data Retrival Ratio			✓
	Consistency	Data Format Consistency			✓
		System Consistency			✓
	Granularity	Temporal Granularity		✓	✓
		Spatial Granularity		✓	✓
Efficiency	Processing Efficiency	Data Processing Efficiency		✓	✓
	Understanability	Metadata and data value understandability			✓
Optional	Credibility			✓	✓
	Currentness			✓	✓
	Accessibility				✓
	Compliance		✓		✓
	Confidentiality				✓
	Tracibility				✓
	Availability				✓
	Portability			✓	✓

Figure 7 - Controllable and Uncontrollable Data Quality Measures

“Formatting” refers to data management system, which includes documentation, naming, grouping, and visualization of data. It is also controllable as the systems can be re-designed or upgraded. Software updates or unifying naming system requires minimal additional costs as well, while demonstrating ability to improve most of the proposed criteria. It is, therefore, recommended to be the first step for building management to work towards data quality.

“Equipment” refers to sensing devices and data transmission hardware. It is controllable as the deployment of sensors is decided by BMS consultants or facility managers. Replacement of existing sensors with those with better performance can significantly improve data quality (as shown in table above.) However, it is limited by capital resources allocated to data collection.

“Condition” refers to unanticipated events that influence data collection. An example can be sudden bursting of water pipes, thus affecting the flowrate measured. It is usually not controllable, as such circumstances are not prepared for. The proposed framework raises the awareness of the unexpectedness of reality that can severely impact data analysis. It pushes relevant stakeholders to think outside normal operation, and perhaps review existing building service and BMS designs so that higher level of data resilience can be built.

8. Limitation of study

The limitations of this study are listed below:

- The case study's data quality performance evaluation is not fully disclosed due to data confidentiality.

- The case study demonstrates the practicality of the framework in applying to conventional building service and management systems. Broader applications need to be done to prove it works on unique infrastructure and building projects as well.

- In view of the rapid pace of technological development, the proposed framework requires constant update and review to stay in line with upgraded sensing equipment and BMS designs. Apart from hardware progressions, the framework needs to prove resilience towards software application advancement. Data collected currently is highly accountable for A.I. Maturing. The standard needs to be raised regularly to ensure only data of high quality is fed into A.I. training. [4]

9. Conclusion

The implementation of a data quality framework is crucial for BMS designs and RCx projects. It ensures that the data collected and analyzed is accurate, reliable, and consistent for effective energy management strategies and improved decision-making. This paper summarizes previous findings and develops a practical framework for BMS data quality evaluation. Criteria with their measurement metrics are explained. This case study of MTRC Elements serves as a push for data quality to be actively valued and considered in the building industry. It demonstrates the importance of embedding a critical assessment framework of data quality by identifying the potential risks and pitfalls that may occur in O&M and RCx building performance analysis.

It was demonstrated in this study that a consolidated framework for data quality assessment has a critical role in shaping the future of building performance management.

10. Future Directions

A rising demand for data quality policies and framework is expected to provide guidance to promote clarity in data communication. Standardized naming eliminates ambiguity and enables correct interpretation across different building service systems, where unified abbreviations and documentation formats reduce potential errors. A guideline should be published, widely shared, and regularly updated to reflect additions or updates to building equipment. It should also be publicly accessible and receptive to critique. Efforts from the entire building sector are required to foster industry-wide initiatives, collaborations, and knowledge sharing.

Authorities can play a part in enhancing awareness of data governance. Training programs can educate stakeholders on the broader impacts of data quality and encourage best practices. Forums can effectively facilitate conversations and consensus to be created between stakeholders.

More capital is expected to be invested in the development of digital devices. This can be a major drive to enhance sensing device technology through research and development for higher accuracy and resolution, benefiting the whole industry.

To convince stakeholders to realize the value of data quality, it is essential for RCx teams to highlight the importance to address the discrepancy between measured and actual energy performance, with a strong emphasis on the long-term benefits a strong evaluation framework can bring to establish a solid foundation for future projects and facilitate scalability, sustainability commitments, and on-going success.

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