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Smart Building Synergy: Integrating IKB and IoT for Enhanced Energy Efficiency

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-ABSTRACT-

Ageing or under-maintained equipment is usually expected to perform less efficiently than a new equipment. In this paper, plant efficiency (kW/RT) is used as an energy efficiency indicator. Data analytics, based on aggregation operations, filtering and forecasting, allows us to obtain knowledge from chillers and the equipment, to prescribe the appropriate maintenance strategies. The Energy Management System (EMS) that implements these rules establishes when a chiller stage up/down or flow rate increase/decrease according to different efficiency criteria with respective to cooling demand. A data-driven integrated strategic and sustainable asset management practices via green and smart facility management concepts, enabled an 11-year chiller plant in an educational institution in Singapore to perform more efficiently with lower carbon footprint as compared to when it was first installed in year 2010.

KEYWORDS;- *Smart building, energy efficiency*

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I. INTRODUCTION

In the present era, businesses face intense competition and must strive for superiority to capture market shares and achieve an economic edge over their rivals. Even with a robust maintenance process, costs may escalate due to various factors, such as the challenges associated with acquiring replacement parts. Additionally, inadequate maintenance strategies, such as insufficient lubrication practices, can contribute to cost escalation. However, if a company adheres to established service standards and effectively maintains its machinery and equipment, even aging assets will have minimal impact on operational equipment effectiveness, reliability, uptime, and life cycle costs [1]. Ongoing research focused on enhancing equipment performance primarily emphasizes technological approaches, while neglecting a comprehensive investigation of the influence of maintenance strategies. From this standpoint, the integration of Integrated Knowledge-Based (IKB) digital twin and physical asset management [2] is indispensable for ensuring that a company's assets retain their value and continually optimize their quality and performance. Physical asset management, aided by the IKB framework, encompasses critical activities and frameworks that assist organizations in effectively managing their assets. Failure to do so can result in deteriorating asset performance and increased rates of asset failure. The educational institution facility can accommodate a total of 7,200 full-time students, 8,100 part-time students, and 650 staff members. In order to fulfil the requirements of the contract, a 27-year Public Private Partnership (PPP) agreement is necessary. This contract entails the provision of comprehensive facilities management services upon the completion of construction in June 2010. A key stipulation outlined in the contract specifications is the need for a dependable and energy-efficient building. It is crucial to note that the energy consumption of the chiller plant accounts for a significant portion of the overall building energy cost. To ensure the optimal functioning of the plant throughout the duration of the contract until the year 2035, a team of 5 individuals is designated to manage the monthly utilities operational cost, with the aim of maintaining the plant efficiency below 0.65kW/RT (Green Mark Platinum Standards). Moreover, it is important to consider that the Capital Cost associated with the replacement of HVAC equipment represents a substantial portion of the life cycle budget [3]. Consequently, it holds great significance if assets can sustain optimal performance beyond their intended retirement age. The primary objective was to create an Integrated Strategic Asset Management Plan (ISAMP), wherein the Asset Management Plan (AMP) served as the catalyst for change and the development of Asset Management (AM) capabilities within the organization.

Table 1. ISAMP Development Timeline

Key Activities	2015	2016	2017	2018
Develop a comprehensive list of asset register and collate quality chiller plant performance data	X	X	X	
Competency Development for Certified Asset Managers			X	
Develop Strategic Asset Management Plan (SAMP) and Asset Management Plan (AMP)		X	X	
Train data analyst to analyse chiller plant data			X	X
Enhance of chiller plant operational performance based on data analytics				X

Our research and project methodology as shown in Figure 1 comprises three essential directions:

1. A knowledge-based digital-twin approach to the IoT-driven integration of HVAC data
2. A risk management Asset Intelligence approach by merging data, information and technology to forecast the life cycle energy cost and performance of HVAC plant assets.
3. A proactive ontology-based framework for asset management

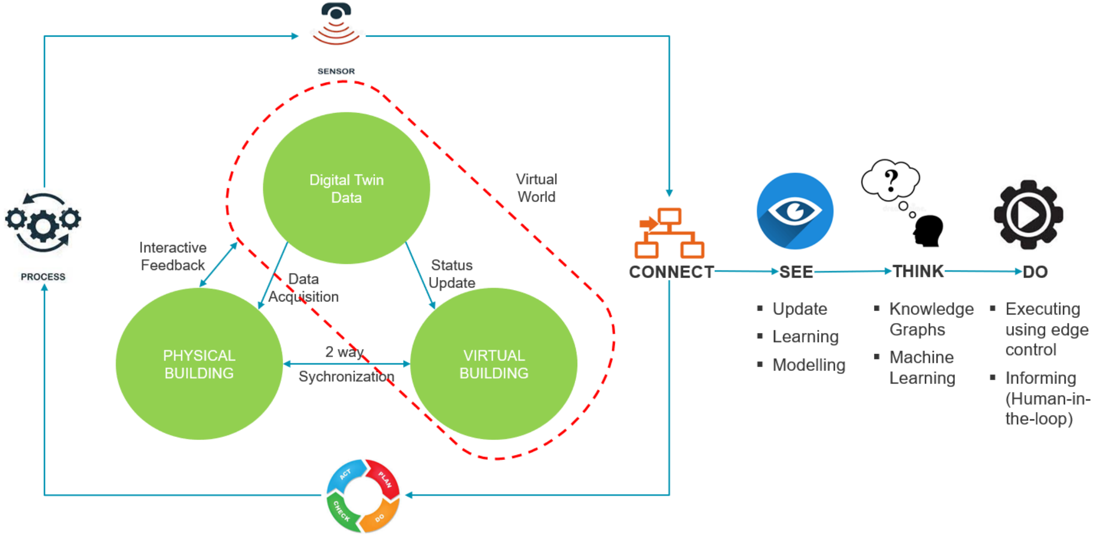

Figure 1. IKB Digital Twin and IoT-Driven Approach

A knowledge-based methodology for integrating good quality HVAC data in the context of the Internet of Things (IoT) [4] has opened up new possibilities and strategic directions, resulting in increased efficiency, effectiveness, and productivity in maintenance management operational processes. This paper aims to explore the potential of integrating IoT and other data structures in smart buildings to manage and share the vast amount of data generated by HVAC systems and equipment [5]. It also addresses the ongoing challenges in this field. A well-designed and well-executed IoT and Integrated Knowledge Based framework can facilitate informed decision-making for asset investment, energy efficiency, and asset life extension. However, despite the paramount importance of a comprehensive life cycle approach to asset management, there is limited guidance available on how to develop such an approach in the literature and ISO55000 standards. The Integrative Strategic Asset Management Plan (ISAMP) plays a crucial role in the asset management service culture and document hierarchy. It aligns organizational objectives with strategic asset management and outlines the necessary high-level actions in areas such as finance, risk management, and sustainability to ensure the achievement of asset management goals. According to Berger [6], the digitization of assets has increased their value to organizations and highlighted the need for better maintenance using tools like the Computerised Maintenance Management System (CMMS). Integrated Strategic Asset Management encompasses cost optimization, building and engineering services, information technology, operational technology, sustainability, and human factors, providing a holistic approach to delivering built assets [7]. This approach recognizes the interconnectedness of these elements and aims to optimize cost, performance, and risk while addressing immediate operational needs and considering long-term management direction for building services and engineering assets. An ontology-based Integrated Strategic Asset Management Framework [8] Lifetime Impact Identification Analysis (LIIA) [9] was adopted in our project. This is a tool to identify change impact in Asset Life Cycle Management (ALCM) leading to the need to update the Asset Life Cycle Plans and Strategies.

The primary driving force behind the notion of integrating knowledge-based and IoT-driven approaches to energy conservation is the utilization of data-centric technologies [10]. The need for enhanced operations is determined by the capacity to enhance machine uptime and availability, as well as the importance of doing so. Therefore, the optimal application of smart buildings lies in the examination of data-driven, analytic systems, which are utilized in conjunction with building equipment maintenance strategies and structures [11]. The significant contributions in the realm of smart asset management and big data are implemented within the maintenance environment, where data sets and system requirements are explored to incorporate equipment maintenance applications in a smart building setting [12]. This research concentrates on the information system model that offers a scalable big data pipeline for the integration, processing, and analysis of building data. The contribution of this research is assessed within the framework of the evolving building environment and infrastructure, where both legacy (e.g., automation controllers installed in 2010) and emerging instrumentation (e.g., internet-aware smart sensors installed in 2019) must be supported and integrated to enhance initial smart building endeavors [13].

II. APPROACH AND METHODOLOGY

A In this article, we present a methodology driven by data to establish, enhance, and optimize the regulations of an Energy Management System (EMS) in order to improve energy efficiency in multiple-chiller plants (refer to Figure 2). The analysis of data yields, on one hand, insights into individual chillers and, on the other hand, insights into the chiller plant. The objective of analysing chiller data is to augment the efficiency of each individual chiller, while the objective of analysing plant data is to enhance the overall efficiency of the plant. The knowledge gained about the performance of individual chillers serves two purposes: adjusting the internal parameters of the chillers and defining or optimizing the rules implemented in the EMS. In order to achieve this, conditional rules (If-Then-Else) are employed to determine when a chiller should be operated at a higher or lower stage, while sorting rules based on multi-criteria rankings are used to determine which chiller should be started or stopped (the most suitable chiller in each given situation). Ultimately, the knowledge extracted from the plant allows for the updating of the management rules. Our approach is founded upon a hierarchical multi-level control system [14], which necessitates the implementation of the coordination level (an expert system with the management rules) and certain configuration actions within the local units (chiller control boards).

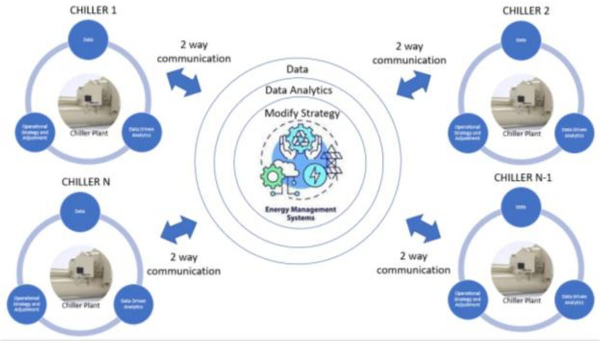

Fig 2. Methodology for extracting knowledge and enhancing efficiency in chiller plant

In our approach, average and counting samples are used as aggregation methods. Measures (the object of analysis) are energy efficiency indicators such as chiller and plant COPs, power demand and cooling load. Attributes are outdoor temperature, chiller load ratio, type of chiller, number of chillers running, year, month, day of year, weekday, hour, etc. Finally, data can be selected either from a specific chiller or from the plant. The attributes listed above can be also used to filter the data. For example, data from a specific weekday (Monday), hour interval (0–8 h), outdoor temperature limit (Outdoor Temp<30℃), etc. Expression (1) summarizes some operations which can be carried out in different data analyses.

$$\Sigma \begin{bmatrix} \text{Cooling Demand} \\ \text{Power Demand} \\ \text{Heat Map} \\ \text{Occupancy Level} \\ \text{Heat Balance} \\ \text{COP}_{\text{equipment}} \\ \text{Plant efficiency} \end{bmatrix} \prod \begin{bmatrix} \text{Year} \\ \text{Day of Year} \\ \text{Month of Year} \\ \text{Weekday} \\ \text{Weekends} \\ \text{Hour} \\ \text{Short term forecast} \\ \text{Outdoor Temperature} \\ \text{Chiller Type} \end{bmatrix} \prod \begin{bmatrix} \text{Chiller 1-n plant} \\ \text{Any other site limitations} \end{bmatrix} \tag{1}$$

Data projections can be accomplished utilizing visualization techniques through the utilization of Microsoft PowerBI and EMS Dashboard to incorporate additional information. Additional variables such as condensing pressure and temperature, compressor current, and others can also be incorporated in the data analysis of each chiller. In this particular case, the inclusion of their information in the form of simple time-series plots can aid in the monitoring of chiller behavior. Based on the knowledge acquired regarding the performance of each chiller, recommendations can be made regarding modifications in its internal configuration settings. The control of the internal chiller is carried out by the Original Equipment Manufacturer (OEM), which only allows us to adjust schedules and setpoints within a specific range. Parameters such as output water temperature, control zone, rate of changes, slide percentage, delays, and others can be adjusted to enhance chiller efficiency through the Energy Management System. Data-driven analysis also provides insights into how attributes impact the efficiencies of both the chiller and the plant. This knowledge is then transformed into management rules, which are implemented in an expert module of the Energy Management System (EMS). In this regard, the extracted knowledge is utilized to configure chillers, update the set of conditional rules, or modify their sorting criteria, resulting in appropriate plant management strategies. The Building Management Team (BMT), responsible for energy management in the building, should actively participate in the data analysis process and in the definition or adjustment of management rules. Their expertise can be leveraged to validate and approve the management rules prior to their deployment on controllers. The strategies to decide when chiller stages up/down can be implemented using basic programming structures, executable by any building management system (see Expression (2)).

$$\textbf{If} \begin{bmatrix} \text{Condition 1} \\ \text{Condition 2} \\ \text{Condition 3} \\ \dots \\ \dots \\ \text{Condition X} \end{bmatrix} \textbf{Then} \begin{bmatrix} \text{Action 1} \\ \text{Action 2} \\ \text{Action 3} \\ \dots \\ \dots \\ \text{Action 4} \end{bmatrix} \textbf{Else} \begin{bmatrix} \text{Opposite Action 1} \\ \text{Opposite Action 2} \\ \text{Opposite Action 3} \\ \dots \\ \dots \\ \text{Opposite Action 4} \end{bmatrix} \tag{2}$$

These strategies constitute an expert module that determines the actions the EMS (Chiller up/down, up/down disable and no change) performs on the chiller in operation, according to the set of rules and sensor data in every situation. As an example, these management rules could be expressed according to Expression (3):

$$\textbf{If} \begin{bmatrix} \text{Cooling Load} < \text{900RT} \\ \text{Outdoor Temp} > \text{32C} \\ \text{Chiller Load} > 0.9 \\ \text{Mth} < \text{Jun AND Mth} < \text{Oct} \\ \text{Hour} >= \text{8am AND Hour} < \text{3pm} \end{bmatrix} \textbf{Then} \begin{bmatrix} 2^{\text{nd}} \text{ Chiller load up} \\ \text{Increase VSD rate by x\%} \\ \text{Any other actions} \\ \text{No Change} \end{bmatrix} \textbf{Else} \begin{bmatrix} \text{Ramp down chiller} \\ \text{Decrease VSD rate by x\%} \\ \text{Any other actions} \\ \text{No Change} \end{bmatrix} \tag{3}$$

III. CHALLENGES AND IMPLEMENTATION ISSUE

The project started with the initial solution to thoroughly understand the problem context. After several discussion sessions with the site operational team and HQ management and planning team, it was concluded that the eight (8) main problems are: -

1. Integral view of holistic asset management does not exist
2. Decision Support Tools (DST) are made based on individual discipline and functions. Data are not shared
3. Limited insights to remaining useful life of asset beyond 3 years
4. Inconsistent data collection standards
5. Context of data collection
6. Lack of training in data collection

7. Lack of quality assurance processes.
8. Changes to definitions and policies and maintaining data comparability.

Underlying this problem statement lay several causes.

i) Limitations in the availability and reliability of data impeded our efforts to forecast equipment conditions.
ii) Policy statement is inadequate and there were 7 volumes of document, but it does not create an integral understanding of the assets.
iii) "Asset Managers" working on site had technical education and many years of operations but limited insights to other topics (financial, risk management and sustainability and data analytical skills).
iv) Different divisions and departments were dealing with different aspects of the assets and not always shared throughout the organization. Hence limited the integrated overview of the assets.
v) "Asset" Managers indicated a big part of their time was consumed by all kinds of operational question and short-term priorities. This limited their ability to develop an integral overview of the remaining useful lifetime of the assets.
vi) Assessing of lifetime impact of the asset based on different maintenance and operational scenarios.

The introduction of high volumes of imperfect, "noisy" plant operating data into the model often causes these theoretical performance models to fail. [15] These models — which worked in the lab — return inaccurate results when faced with real-world operating data. "Inaccurate" results can mean no results at all, or it can mean results that have low statistical confidence and thus should be ignored. We cannot let imperfect operating data keep us from reliable and accurate performance monitoring of chiller plants. Since the cost of delivering laboratory-quality data to our data models is too high, we need to let go of the dream of perfect data and deal with the messy data we have. Our performance models need to work well despite the noisy plant operating data that comes from our chiller plant real-time performance. Hence quality data is obtained 90% of the time, imperfect or noisy data can be assumed to be within the acceptable boundaries of uncertainty. Two types of approaches exist that we used: -
i) Detect and remove outliers from the data.
ii) Impute missing values in our data (that could also have been outliers that were removed) [16].

IV. RESULTS

In this paper, a comprehensive methodology for improving the efficiency in multiple-chiller plants has been proposed. This methodology is based on a data analysis of the operation of the chillers and the overall plant, using real data instead of simulations. The proposed data analyses highlight relevant information by applying aggregation, filtering, and data projection. Using the knowledge extracted specifically from the plant, control parameters of the chillers can be adjusted, and management rules can be defined or tuned. The aim is to achieve efficient management of the plant, without the need of incorporating cutting-edge controllers, since the management rules obtained through the proposed approach can be easily deployed in existing controllers.

Year 2017 – Pre-Implementation Period

The energy audit performed at ITE College West from 20/01/2017 to 26/01/2017 for 24 hours are as follow. The operating efficiency of existing condenser water pumps was observed to be 23% poorer (0.070 kW/RT) than the design requirement stipulated in Singapore Standard SS553 for platinum standards (0.057 kW/RT). It was noted that the existing condenser GPM/RT (3.58 GPM/RT) is 19% higher than the design value of 3.00GPM/RT, suggesting over-pumping. Figure 3 and 4 shows the kW/RT and scattered plot of chiller plant performance in 2017.

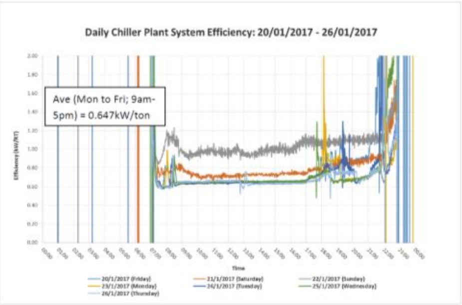

Fig 3 Superimposed plot of Daily Chiller Plant System Efficiency kW/RT

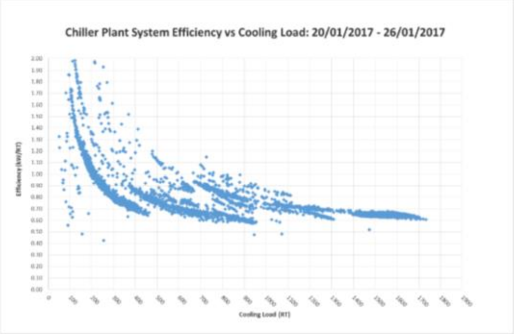

Fig 4. Scatter Plot of Chiller plant efficiency over cooling load

Heat balance in accordance with AHRI 550/590. over the entire normal operating hours with achieve 83% of the computed heat balance within ±5% over the audit period (1 week).

Year 2019 – Post Implementation Period

The chiller plant system efficiency during the building's normal operating hours (Weekdays, 9am to 6pm) is 0.559 kW/RT, with the component efficiency of Chiller – 0.451 kW/RT, Chilled Water Pump (CHWP) – 0.040 kW/RT, Condenser Water Pump (CWP) – 0.042 kW/RT and Cooling Tower (CT) – 0.026 kW/RT. The average cooling load during the peak hours is 1,693 RT. Figure 5 and 6 shows the kW/RT and scattered plot of chiller plant performance in 2017.

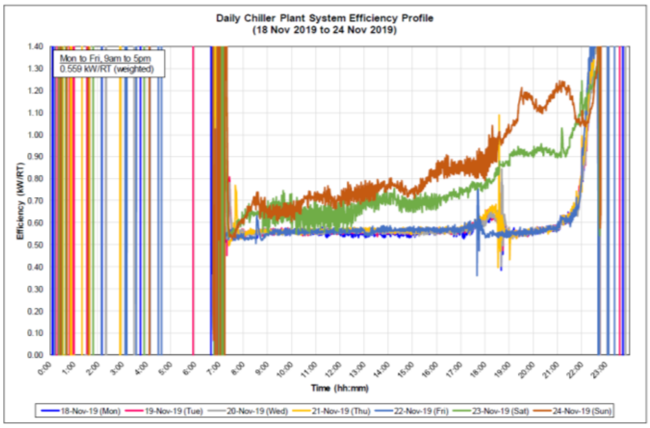

Fig 5. Super-imposed plot of Daily chiller plant system efficiency kW/RT

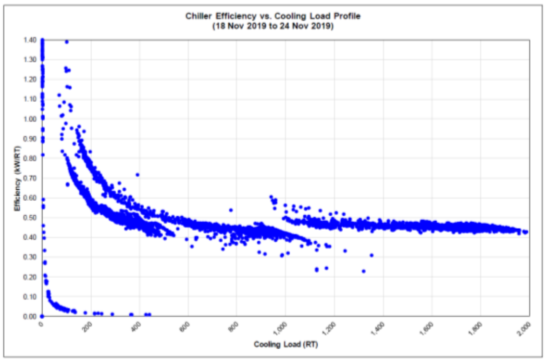

Fig. 6 Scatter Plot of Chiller Efficiency over cooling load

Heat balance in accordance with AHRI 550/590. over the entire normal operating hours with achieve 86% of the computed heat balance within ±5% over the audit period (1 week). This is an improvement of 3%.

Condition Monitoring and Prescriptive Maintenance

The plant efficiency has improved from 0.65 kW/RT (Singapore Green Mark Platinum Standard) in 2013 to 0.56 kW/RT in 2021, as shown in Fig. 7. A significant breakthrough in the way forward for better energy and net carbon management.

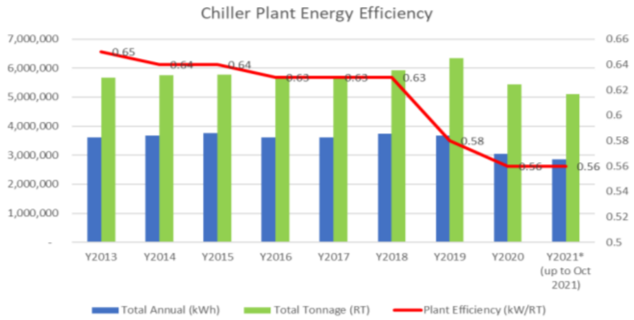

Fig. 7. Chiller Plant Energy Efficiency

Future Development

With the recognition that data plays a central role in effective asset management, we are able to assume authority over the performance of the asset beyond its immediate sphere of influence. In the present day, one of the most crucial solutions for asset management is the digital twin, which serves as a virtual representation of a physical asset. Utilizing the Internet of Things, this amalgamation of the virtual and physical realms enables power and utilities companies to scrutinize data and supervise systems in order to prevent periods of inactivity, cultivate new opportunities, and employ simulations for planning purposes. By transitioning to an approach that prioritizes data, companies can achieve significant efficiencies over time. Notably, the amount of data collected on chiller performance has experienced a substantial increase in recent years, encompassing factors such as flow, temperature and pressure differentials, laboratory data, metering and occupants' usage patterns, engineering and construction data, as well as asset performance and maintenance data. This assemblage of data serves as a valuable source of intelligence that allows for the monitoring and control of assets from procurement to retirement, thereby granting organizations the capability to diagnose and address issues before they lead to a disruption in the supply chain. This capacity to take preventative measures, forecast future asset performance, and mitigate risk contributes to the enhancement of investment decisions. However, a challenge arises due to the concurrent need to concentrate on both short-term operational matters and long-term strategic topics. Furthermore, the future competence of maintenance and operational staff may become contingent upon the prominence of Artificial Intelligence and Machine Language in guiding operational decisions.

V. CONCLUSION

The Integrated Knowledge-Based (IKB) and IoT-Driven Approach remains a relatively nascent concept within the realm of asset management in the built environment. This approach amalgamates the domains of asset management, technology management, and organizational decision-making. By doing so, it emphasizes the potential for market competitiveness. The implementation of this approach necessitates an enhancement in the management of assets within a "techno-organizational environment." This environment enables asset managers to consistently monitor assets and retrieve asset knowledge in an automated manner, whether the knowledge is generated internally or externally to the organization. Consequently, this establishes a foundation for improved and efficient asset decision-making, with the potential for external support. The connection of assets entails the integration of operational technology with information technology, the cultivation of a profound understanding of an organization's physical assets, and the possession of high-quality and reliable data. Such data can then be utilized to generate the insights necessary for incremental and enduring business enhancements. The advent of the Internet of Things (IoT) has given rise to new data streams that can aid in decision-making and facilitate the connection between assets and other sources of real-time intelligence. IoT and other innovative tools can enable scenario planning and predictive assessment of asset performance. However, if these tools are deployed in isolation, they may fail to deliver the desired commercial advantages. In this paper, we have demonstrated that the incorporation of technological intellectual capabilities can enhance asset management within an organization. Smart asset intelligence is predicated on the ability to directly retrieve the required information from the asset itself. This information may encompass a variety of aspects, ranging from a distinct identifying name to the operational state of the asset, or even the way the asset is employed, such as automated maintenance.

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