Journal of Advances in Information Technology, Vol. 15, No. 9, 2024

Smart Technologies for Whole Life Asset Management

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***Abstract*—Smart technologies spilled over from Industry 4.0 has benefited many sectors in the built environment. Digitization of information and digitalization of processes facilitated many advances in whole life cycle asset management. During uncertain times, smart technologies increasingly enable asset managers to better manage their assets with a life cycle approach. This paper studies the technology trend in facilities asset management. Next, the importance of managing change and resilience planning in whole life cycle asset management is explained. Finally, strategies using smart technology to strengthen resilience and manage change is present.**

***Keywords*—asset management, digitalization, Industry 4.0, resilience, smart technologies**

I. INTRODUCTION

Asset Management (AM) is the coordinated activity of an organization to realize value from assets, where asset is defined as an item, thing or entity that has potential or actual value to an organization, with critical asset as an asset that have the potential to significantly impact on the achievement of the organization's objectives [1]. International Facility Management Association (IFMA) [2] defined that in the context of built environment, assets are typically managed by facilities managers. The International Facility Management Association defines Facilities Management (FM) as "a profession that encompasses multiple disciplines to ensure functionality, comfort, safety and efficiency of the built environment by integrating people, place, process and technology". In the same way, International Business Machines Corporation (IBM) [3] defines FM as "the tools and services that support the functionality, safety, availability, reliability and sustainability of buildings, grounds, infrastructure, and real estate". While the former definition focused on FM being the profession, the latter definition centered on the technology and process development.

FMA Australia [4] FM industry is a decades old practice generally recognized to have started during the 1970s when services are provided by cleaners and caretakers of buildings. Over time, FM has evolved to becoming a profession that is multi-discipline which involves technology, people, space and process. In the life cycle of a building, the FM phase is the longest of approximately 30 years and is also the phase that generates the most expenses. Marocco *et al.* [5] highlighted that the construction phase of a building takes up about 15% of the total life cycle cost while Jordani *et al.* [6] and Parsanezhad *et al.* [7] stressed that operation phase accounts for most of the cost with more than 60% in both cost and time, depending on the type of building.

To help with the management of facilities and assets, facilities managers are increasingly turning to technologies. Barwise *et al.* [8] observed that the trends that enabled smart FM technologies to be started with the extensive digitization and automation of our modern age since the 1950s, when IBM introduced digital computing to the world. For the next 70 years, Redlein *et al.* [9, 10] and Wong *et al.* [11] highlighted that FM services for management of buildings and facilities have transformed and improved to take advantage of this revolution. Nosalska *et al.* [12] stressed this process has even been accelerated in recent years, coinciding with the start of Industry 4.0 in 2011

Geissbauer *et al.* [13] suggested that the framework of Industry 4.0, which started with the manufacturing industry focuses on "end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners". The three pillars supporting this framework are: 1) Digitization and integration of vertical and horizontal value chains, 2) Digitization of product and service offerings, and 3) Digital business models and customer service management and access. With digitization, many processes are digitalized, and as a result, a significant amount of data is generated. To extract meaningful information from data with pattern and foresight, data communication become an inseparable enabling technology.

Coincidentally, Bjerke *et al.* [14] observed that the start of Industry 4.0 happened around the same time as the

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Manuscript received January 11, 2024; revised March 5, 2024; accepted May 20, 2024; published September 25, 2024.

doi: 10.12720/jait.15.9.1079-1088

transition of 3G to 4G cellular network that started at the end of 2009 and accelerated in 2011. With these advancements in wireless communications and digitalization of processes, the industry also shifted its focus from data acquisition to data analysis and management of data.

This spillover of Industry 4.0 technologies to other sectors like FM industry, accompanied by advances in infocom management, allows the adoption of smart technologies in managing assets. In the field of whole life asset management, technology is becoming increasingly indispensable in recent years, especially during times of crisis such as the pandemic where manpower and operations are affected. Having witness how manpower shortages disrupt operations, it is ever critical to manage change and have resilience plan in place for different technologies domain to work together and to ensure whole life asset management processes are not affected.

In this paper, a review of the trend of smart technologies in the recent decade for FM is carried out. This gives an overview of the asset transformation that is taking place in the industry. Next, technologies that are relevant and beneficial to FM Whole Life Cycle (WLC) asset management are documented.

This is followed by listing down the relevant beneficial technologies related to FM and categorized into: (1) efficiency, (2) sustainability, (3) safety and security, (4) customer service, and (5) Reliability. These categories are chosen as they are most mentioned and desired for service excellence. They are also central to the facilities life asset management. Finally, an account of how smart FM technologies could help establish a framework for managing change and resilience planning during the whole life asset management presented.

In this paper, a detailed report on how Industry 4.0 influences Smart FM is discussed. With the technologies that are available and becoming available in the coming future, a framework for managing change and resilience planning during the whole life asset management is proposed. This framework builds on using technologies (both hardware and software) to form a working model to allow facilities managers to better manage change and plan for resilience in the new future.

This paper is organized as follows: In Section II, technology trends in facilities asset management is reported. Following this, in Section III, how change is managed and planning for resilience in whole life asset management technologies are presented. In Section IV, the strategic aspect of asset management and facility management 4.0 is discussed. Section V concludes this paper.

II. TECHNOLOGY TRENDS IN FACILITIES ASSET MANAGEMENT

A. *Technologies Extended from Industry 4.0*

The first industrialization happened about 200 years ago between late 1700s to early 1800s. This stage of evolution of industry moved away from human and animal labor to water or steam powered machines and other machine tools. In the next evolution in the early 1900s, machines are powered by electricity, which enables the concept of mass production to increase productivity. In the third evolution beginning in the 1950s, electronics and computers started to take over electromechanical systems to enable more digital and automation-based systems. In the most recent Industry 4.0, digitization of data/information and digitalization of processes boosts productivity and the engine of growth to a whole new level.

According to Greissbauer *et al.* [15], digitization of information and digitalization of processes forms the basis of Industry 4.0, which enables our modern-day data analytics, Building Information Modeling and automation. Fig. 1 shows the framework of Industry 4.0.

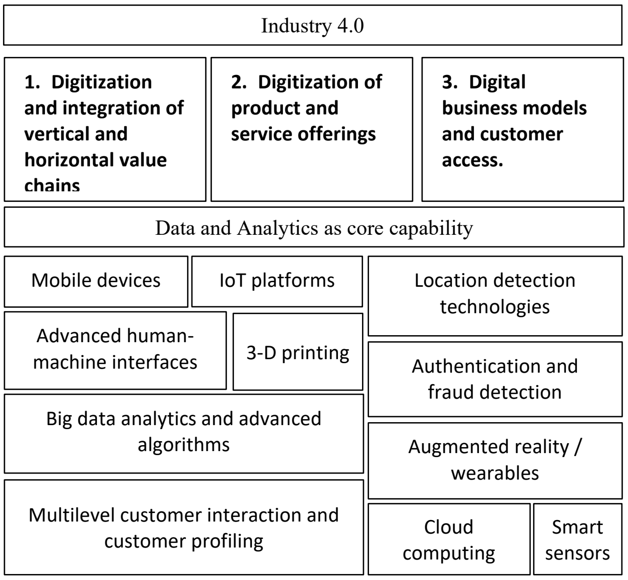

Fig. 1. Industry 4.0 framework and supporting technologies adapted from Greissbauer [15].

Geissbauer defined that Industry 4.0 “focuses on the end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners.” The three pillars supporting this framework are (1) Digitization and integration of vertical and horizontal value chains, (2) Digitization of products and services offerings, and (3) Digital business models and customer access.

The first pillar, “Digitization and integration of vertical and horizontal value chains” represents the integration processes within the organization and with partners, stakeholders, suppliers and customers outside of the organization.

The next pillar, “Digitization of product and service offerings” refers to the expansion of existing products and services with technologies that enables creation of digital data, communications and analytics for integration of facilities solutions.

The intention of the last pillar, “Digital business models and customer centric and access” is to increase revenue and/or customer satisfaction by providing additional or new digital products and services to serve customers. Finally, holding these three pillars as an integrative entity, is leveraging on digitization to achieve data analytics as core capabilities of the organization.

The encompassing principle behind the three pillars of digitization is the development of data and analytics as the core capability and core competencies of an organization. Using the digitized means, system and facility data are easily available to enhancing the operations of FM in key areas such as efficiency, effectiveness, sustainability, safety, security, and customer experience. Building around this key data and analytics principle, the supporting technologies are, Mobile devices, IoT platforms, Location detection, Advanced human-machine interfaces, Authentication and fraud detection, 3D printing, smart sensors, big data analytics and advanced algorithms, Multilevel customer interaction and customer profiling, augmented reality/wearables, virtual reality, and cloud computing.

Over the past decade, adopted technologies are focusing on enabling this digitization transformation and transition. As a result, the technologies that are the most adopted is IoT enabled smart sensors. This technology consists of physical components that make buildings smarter and greener such as installing IoT enabled sensors (temperature, humidity, CO_2, light and occupancy etc), card and biometric security access systems, cameras and imaging systems, energy and water smart and advance metering with sophisticated gateways. Along with IoT enabled sensors, IoT platforms, mobile devices and cloud computing are also adopted as accompanying wireless technologies. In fact, in many industries, this adoption is still actively being pursued due to better economic feasibility in recent years.

This shows that the key technologies adopted from Industry 3.0 and 4.0 are the digitization of information which leads to the digitalization of development processes. When translated to asset management, these "smart technologies" empowers managers to be more proactive, predictive and productive, less reliant on manpower and higher management quality of their assets. In managing changes and resilience planning of assets, "smart technologies" from Industry 4.0 also create a more systematic and predictive solution that takes care of their whole life cycle.

B. Wireless Communications Evolution

One of the driving forces behind the rapid evolution of digitalization of processes is the interconnectivity of devices/equipment among and between systems. This is especially so when wireless technologies became mainstream in the early 1990s.

Atta *et al.* [16] classified wireless technologies for the built environment according to their coverage area such as Personal Area Network (PAN), Home Area Network (HAN), Local Area Network (LAN), Metropolitan Area Network (MAN), and Wide Area Network (WAN). Wireless data connectivity for asset management, wireless technologies can be classified into broadly two categories: namely 1) cellular networks and 2) non-cellular networks. Cellular Networks incur subscriptions for the users, but base stations installation and maintenance are taken care by telecommunications companies. Non-cellular networks, on the other hand, do not generally incur subscription for the users, but require them to install and maintain base stations or alike on their own. There are, however, some technologies in the recent decades such as some LoRa networks and Sigfox that provide cellular-like solutions to users, at a much lower data and subscription rates.

For cellular mobile technology, the evolution of this network has moved from the first generation in the 1980s to the current 5th Generation 5G. Table I shows a summary of the key features as defined by Alsabah *et al.* [17] for each generation of the mobile network adapted and modified from Atta [16].

TABLE I. KEY FEATURES OF EACH GENERATION OF MOBILE NETWORKS [17]

Key Features	**1G**	**2G**	**3G**	**4G**	**5G**
Year	1980–1990	1990–2000	2000–2010	2010–2020	2020–2030
Technology	Analog	Digital	Digital	Digital	Digital
Modulation Scheme	FDMA	TDMA, CDMA	CDMA	CDMA, OFDMA	OFDMA, BDMA
Switching	Circuit	Circuit, packet	Packet	Packet	Packet
Data Rate	2.4–14.4 kb/s	14.4–64 kb/s	2.1–14.7 kb/s	100 Mb/s –1 Gb/s	1 Gb/s and above
Bandwidth	150 kHz	5–20 MHz	25 MHz	100 MHz	1–2 GHz

One main evolution feature of the cellular network is the increasing data rate and bandwidth. With the transition from analog to digital, and using more advanced modulation techniques, the transmission speed and size of data has evolved from 2.4 kb/s to a remarkable 1 Gb/s.

To understand the significance of this advancement in cellular technology, a project that was undertaken by the authors is used as a case study example. In this project, a campus in Singapore (Republic Polytechnic) with 20 buildings has a requirement to monitor 170 water meters every minute. The data generated per meter per month is about 1.5 MB. The total data from this campus is about 3 GB per year. To transmit this annual water consumption data using the existing 3G/4G network, it will take up to 130 days. However, if 5G cellular network is used, the transmission time is less than 23 s. This significant improvement in connectivity enables other technologies that can benefit asset management such as real-time data synchronization, data analytics, and machine learning, and central anomalies detection to materialize.

To overcome the challenges of cost and volume of data generated, we deployed local wireless mesh network of sub-GHz that allows reliable wireless connectivity and no recurring costs. In this way, every single pipe in the campus is monitored, giving FMs high resolution clarity of the piping health of the campus, as well as the user behavior of occupants of the buildings. The limitations, however, is that if the campus is to increase in the size significantly, the design of the local wireless mesh network must be changed to accommodate more data without impacting the performance of the network.

Beale *et al.* [18] highlighted that Narrow Band-IoT (NB-IoT) and LTE for Machine type of communication (LTE-M) are two leading technologies based on cellular network that brings a balance between coverage, latency, battery life and capacity. Although the data rate is not as high as the standard cellular generation networks, NB-IoT and LTE-M strike a good balance between costs and speed for sensor networks, especially in buildings.

For non-cellular wireless technologies, they are limited by operating within the Industrial, Scientific, and Medical (ISM) bands namely, 433 MHz, 868 MHz, 915 MHz, and 2.4 GHz. In general, those technologies that operate in the sub-GHz range (i.e., 433 MHz, 868 MHz, and 915 MHz) have lower data rates but has a wider coverage range. The range is mostly limited by the output power permissible under regulations set out by the governing authorities of each country. For example, in Singapore, Radio Frequency (RF) spectrum and the respective RF output power is regulated by Info-communications Media Development Authority (IMDA) [19], which regularly publishes assignment policies and application procedures for the various radio-communication services.

Table II shows a list of non-cellular wireless technologies highlighted by Heydarishahreza *et al*. [20] and Li *et al.* [21] that are commonly used and adapted in the built environment. The evolution of non-cellular wireless technologies focuses on either increasing data rate (WiFi) by increasing the bandwidth and using multiple antennas or reducing the power consumption (BLE, LoRa and Sigfox) by decreasing the data rate and lower the RF transmit power. Notable non-cellular wireless technologies in this category in the wireless mesh technologies that links multiple sensors in a mesh interconnectivity to create a self-healing, self-organizing and ease of scalability network. This is most suitable for large sensor network deployments with flexibility for future expansion.

TABLE II. COMPARISON OF NON-CELLULAR COMMUNICATION TECHNOLOGIES [20, 21]

Technology	Spectrum	Data Rate	Coverage Range
Zigbee	2.4 GHz, 868 MHz, 915 MHz	Up to 250 kb/s	30–50 m
WiFi	2.4 GHz, 5 GHz	2–2400 Mb/s	250 m (indoors)
Bluetooth	2.4 GHz	Up to 3 Mb/s	100 m (indoors)
Bluetooth Low Energy (BLE)	2.4 GHz	Up to 1 Mb/s	100 m (indoors)
Z-Wave	2.4 GHz, 868 MHz, 915 MHz	Up to 100 kb/s	30 m (indoors) 100 m (outdoors)
LoRa	433 MHz, 868 MHz, 915 MHz	0.3–50 kb/s	3–8 km (urban) 15–22 km (rural) 15–45 km (flat)
Sigfox	868 MHz, 915 MHz	Up to 1 kb/s	3–10 km (urban) 30–50 km (rural)
Wireless Mesh	Various	Depending on protocols	Depending on deployments

These range of wireless technologies form a wholistic and indispensable part of industries benefitting from Industry 4.0. In asset management, this provides the link between systems for greater automation and autonomy.

C. *Transition from Digitization to Digitalization*

Over the past decade, technologies adopted in the buildings are focused on digitization transformation of their data and information. Due to this emphasis, the technologies that are the most adopted is IoT enabled smart sensors. This technology consists of physical components that make buildings smarter and greener such as installing IoT enabled sensors (temperature, humidity, CO_2, light and occupancy), card and biometric access systems, cameras and imaging systems, and energy and water metering. Along with IoT enabled sensors, IoT platforms, mobile devices and cloud computing are also adopted as accompanying technologies. In fact, in many industries, this adoption is still actively being pursued due to better economic feasibility in recent years.

Redleir *et al.* [22] observed that consistent with the study conducted in 2018 which shows that Sensors / IoT technologies are that are easiest to implement technically, and with the most economical feasibility and shortest pay off period (see Table III adapted and modified from Redleir). According to this study, adoption of a certain technology is also tied to the economic feasibility. As summarized, it can be noted that those technologies that are more hardware based, and lesser software element has shorter technical feasibility timeframe also have shorter economic feasibility timeframe.

TABLE III. TECHNICAL AND ECONOMIC FEASIBILITY OF NEW TECHNOLOGIES [22]

Technology	Technical Feasibility (Maximum Timeframe)	Economic Feasibility (Maximum Timeframe)
Sensors / IoT	0.55	1.79
BIM	1.09	2.24
Mobile Apps	0.45	1.33
Robotics	2.03	3.91
RFID	0.75	1.85
Digitization / Automation	1.73	2.27
Big Data	0.79	2.06
Virtual Reality	1.00	2.42
Drones	2.00	3.52
Augmented Reality	1.58	2.3

From this study, it is also observed that in the past decades, the focus of technologies in facilities/asset management related work are linked to physical devices or equipment that enable digitization or real data analytics. However, there are also some elements of technologies that operate with better software such as enhancing with automation like AI/ML. As we moved away from this phase of digitization (converting data into digital form), there is a shift in the technologies that moves towards more software and/or cloud based adding to the FM decision-making process (data processing).

Bjerke *et al.* [23] observed the shift towards software focused technologies started in 2011, coinciding with the transition from 3G to 4G mobile network that started at the end of 2009, and accelerated in 2011. With these advancements in wireless communications and digitization of information, the industry also shifted its focus from acquiring data to transmission and management of such data. Traditionally, Ali *et al.* [24] stated that FM software systems such as Computer Maintenance and Management System (CMMS) and Computer Aided Facility Management (CAFM) are standalone systems that do not allow straightforward data integration. This de-centralization of data causes difficulty in managing these data. Furthermore, information is fragmented as they are stored in different digital domains, and in some instances still on physical hardcopy record. Therefore, beginning 2011, technologies using software and/or cloud-based solutions also experienced an increase in adoption by the industry including FM.

Marocco *et al*. [25] defined that the technological shift towards software-based technologies can be classified broadly into four areas: (1) Information management, (2) Maintenance management, (3) Energy management, and (4) Emergency/Crisis Management. Table IV adapted and modified from Marocco, summaries the four main areas and their subfields of applications.

TABLE IV. Summary of Technologies by Fields of Application Adapted from Marocco [25]

Fields of Application	Subfields
Information Management	Localizing and tracking building components Storing asset information Advanced visualization and interaction with facilities information
Maintenance Management	Work order management Decision-making processes for maintenance Detecting asset faults and inspecting building assets Predictive maintenance
Energy Management	Real-time energy monitoring Assessing and optimizing energy building performance
Emergency Management	Emergency response and path optimization Hazards monitoring

From this table, it is evident that technologies have shifted from data acquisition to data management in the recent decades. Although this technological shift is towards software-based, many of the underlying technologies that support these software-based technologies are still hardware-based. This is a case of leveraging on the technologies in the digitization phase to enhance the services with improved software capabilities that was not available technologically or economically.

Volk *et al.* [26] observed that from building asset management perspective, the priorities supporting the four fields of applications can be further specified. The top 10 priorities are shown in Table V.

TABLE V. Top 10 Priorities Supporting the 4 Fields of Application

Fields of Application	Priorities
Information Management	1. Data acquisition 2. Data transfer 3. Augmented & virtual reality 4. Data integration 5. Data management 6. Data visualization 7. Cloud database 8. Geographic information system 9. Augmented virtuality 10. Virtual reality
Maintenance Management	1. Building management 2. Maintenance and operation 3. Building service 4. Case based reasoning 5. Asset management system 6. BMS 7. CMMS 8. Building automation system 9. Data collection 10. IoT
Energy Management	1. Energy handling 2. Energy utilization 3. Building energy comfort level 4. Energy efficiency 5. Building energy consumption 6. Data mining 7. Building environmental monitoring 8. Building energy performance 9. Heterogenous data source 10. 3D web browser
Emergency Management	1. Augmented virtuality 2. Building model 3. Disaster management 4. Asset information requirement 5. Navigation 6. Safety 7. Accident prevention 8. Fire 9. Asset information requirement 10. BMS

From these, it is evident that the focus of smart FM has shifted from hardware-based technologies of data acquisition to software-based data visualization, analytics and decision making over the past decade, especially going into 2021 and beyond.

III. Managing Change and Resilience Planning in Whole Life Asset Management Technologies

Asset management plays a key role for assets to cope with the external and internal organizational environment such as the ever-increasing competition, markets deregulation as well as technology innovation and disruption, and risks from other events such as terrorist attacks, natural disasters, pandemic flu, political environment and cyberattacks.

It is important to strengthen the link between resilience and Strategic Asset/Facilities Management through Smart Maintenance 4.0 to ensure continuity in operation and mission success (success in more energy efficiency, lower carbon and excellent service offering).

Roda *et al.* [27] conceptualized that Smart maintenance/Smart FM can be based on four aggregate dimensions—data-driven decision-making, human capital resource, internal integration (internal environment), and external integration (external environment).

Vugrin *et al.* [28] defined a broad range of inter-related domains for assessing system resilience can be listed as: (i) technical, (ii) organizational, (iii) social, (iv) economic, (v) ecological (vi) environment.

Table VI depicts a non-exhaustive directory of those definitions of resilience found in the scientific literature in relevant industries. This variety in defining resilience concept can lead to complexities in interpreting and measuring asset and facilities resilience. The several distinctions and understanding of the concept of resilience are determined by various aspect of the subject matter of a resilient system, is an ongoing study.

TABLE VI. DEFINITIONS OF RESILIENCE

Discipline	Definition	Authors / Ref
Resilience in the built environment	“Digital communication and information technologies were the core of businesses during the COVID-19 pandemic. Technology played an essential role in response to the pandemic and is predicted to be the core strategy for long-term resilience.”	Sepasgozar [29]
	“the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies” (PPD-8 2011) and “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions”	Presidential Policy Directive (PPD)-8 2011 [30]
	The term “community” is also defined in a variety of ways. When considering resilience of the built environment, and supported social functions, a community is an area with defined boundaries under the jurisdiction of a local government, such as a town, city, or county.	PPD-21 2013 [31]
	Community resilience is the ability to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions. Activities, such as disaster preparedness—which includes prevention, protection, mitigation, response and recovery—are key steps to resilience.	NIST 2015 [32]
Resilience to Civil infrastructure Engineering	A recent concept in risk reduction and recovery from extreme events is resilience.”	Gardoni [33]
Resilience in socio-ecological systems	Resilience is the “ability to absorb shocks” or “bounce back”	Holling [34]
Resilience in psychology	Resilience is ‘‘positive adaptability” in anticipation of/in response to shocks	Graber [35]
Resilience in Engineering and Economics	Ability of a system to resist perturbations outside of its equilibrium state and its speed to come back to it	Holling [36], Martin [37]
Resilience in organizational Systems	Organizational resilience is used to describe an integrated approach to delivering business continuity alongside aspects of what many organizations would consider operational risk management. Business Continuity is used to describe the capability of an organization to continue and recover operations following a disruptive incident.	Crask [38]

Organization leaders must adapt to the understanding of the concept of complex, dynamic-adaptive systems and that outcome cannot be controlled through static rules, routines, regulations and compliance (See Fig. 2). An organisation may find it simple to concentrate on the things it believes it has internal control over. An organization's performance can be impacted by uncontrolled elements such as competition, politics, the economy, and even the weather. This contrasts with internal elements that appear to be directly within the control of the organisation, such as personnel, corporate culture, procedures, and funds.

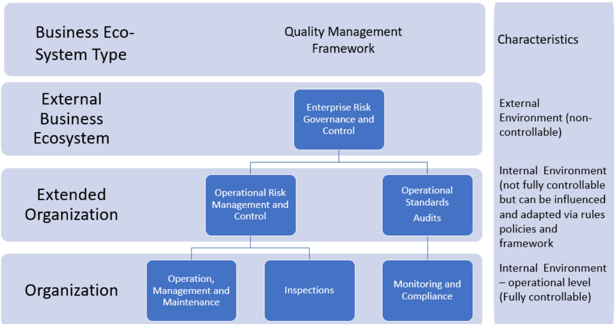

Fig. 2. The hierarchical structure of organisational kinds, quality management system framework and characteristics within a business ecosystem. Adapted from Moore *et al*. [39].

Supply chain management, as well as direct and indirect suppliers that are seen as a component of the larger extended company. The management structure and policies have the power to influence them.

The stability and profitability of a corporation are contingent upon its capacity to promptly detect and react to alterations in the external milieu. Change is unavoidable, and an organization’s ability to adapt to unforeseen changes in the market can make the difference between its survival and demise. As such, it is imperative to take into consideration the external, uncontrollable elements that affect a firm.

Crask *et al.* suggested that empowering operators through knowledge and organization support is a good start. Supporting technical infrastructure that allows operators more time to adapt to systems drifting into disaster and better signals of impeding failure.

Sandra *et al.* [40] argued that we can only achieve levels of resilience by reducing the reliance on compliance-based procedures to create caring relationships. Create a supportive culture that promotes resilient behavior. Culture cannot be managed precisely but it can be influenced.

Komlijenovic *et al.* [41] defined those four common phases emerged from the literature review as shown in the following chart (see Fig. 3). These characteristics involving adapting to shocks and disturbance either by anticipating, protecting or insulating it, adapting to it or recovering from it and restoring operations. It is important to note that the speed of recovery is an important aspect of the resilience concept.

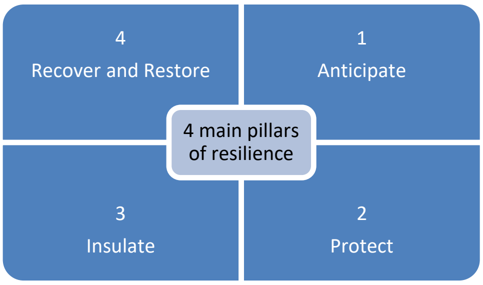

Fig. 3. Four common phases for resilient operations.

Resilience is an approach to deal with complexity and uncertainties, and it should not be considered at component level. It should, however, be viewed as an attribute at the system level to withstand severe conditions.

Organizations need to think about resilience as part of their asset management program. An example is the COVID-19 pandemic that show the world that disruptions or emergencies can happen in a short time and worsen very quickly.

Various design systems react differently to shock events. Figs. 4 represent ways in which systems respond and possibly adapt based on their resilience.

Resilience entails a persistent continuous improvement and adaptation as many aftermath performance levels are likely after recovery.

This general concept of resilience entails four main properties: (i) Rebound (ii) Robustness (the capacity to absorb a shock, to withstand critical functions, to survive after an adverse event: namely protecting and insulating), (iii) Insulate (the capacity to plan for and make ready to withstand a disruption), and (iv) Rapid recovery (the capacity to quickly return to operation and efficiently and effectively following an accident).

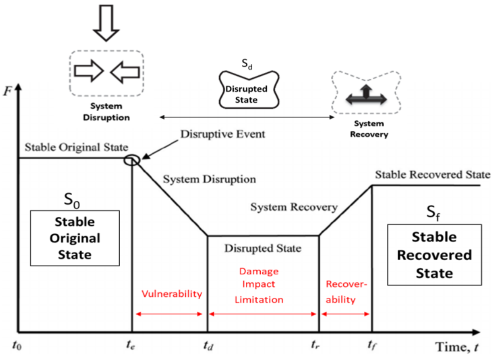

Fig. 4. System state transition in resilience.

Successful organizations are more resilient to predict and react to threats and opportunities in a Volatile, Uncertain, Complex and Ambiguity (VUCA) environment. Hence, resiliency is needed to tackle the complexity of industrial systems and critical infrastructures involving the subsequent dimensions of resilience: organizational, technical or technological, operational, social, economic, financial, reputational, and business model.

IV. STRATEGIC ASPECT OF ASSET MANAGEMENT AND FACILITY MANAGEMENT 4.0

To face the demands of Industry 4.0 and, consequently, minimize the effects of unanticipated failures, hazards, and disruptions in the context of digitalization transition, facilities management is essential. Therefore, one of the primary problems and difficulties with the maintenance function and operations is the ability to forecast asset maintenance needs. By combining dependability, maintainability, availability, and safety (RAMS), the maintenance function seeks to ensure asset dependability, productivity, and sustainability.

In AM and in Industry 4.0, Crespo *et al.* [42] highlighted that maintenance plays a crucial role. Yan *et al.* [43] and Masoni *et al.* [44] stated that predictive maintenance, or Pd.M., is positioned by Industry 4.0 to optimize costs, increase asset dependability, and improve productivity and product quality. Sahal *et al.* [45] and Nordal [46] suggested, it is possible to transition from the conventional approach of routine visual inspection to optimal Intelligent Maintenance, known as Maintenance 4.0. For example, Internet of Things (IoT) sensors installed on building services equipment allow for the monitoring of asset condition and performance. This enables the prevention of failures or issues that could lead to a decrease in service performance or the unavailability of services.

Consequently, connected devices, along with their statuses and performance, can be continuously monitored and tracked in real-time using dashboards that consolidate data from the equipment. This data can then be analysed using AI algorithms, which can trigger automated actions, ultimately leading to performance measurements in Asset Management (AM).

Maintenance 4.0, with the application of new technologies from Industry 4.0 (see Table VII). For example, real-time continuous monitoring of asset condition and performance is made possible by Internet of Things (IoT) sensors installed on strategic equipment on a production line.

TABLE VII. MAINTENANCE 4.0 SMART TECHNOLOGIES

Category	Data Acquisition	Analytics	Visualization Platform	Real-time Adaptive and Automated Control
Energy Management	• Smart IoT Sensors • Building Management System	• Energy Management System • Machine Learning and Artificial Intelligence System • Numerical Methods	• Power BI • AR Devices • Screens/Dashboards • Webpages • Phone Apps	• Edge Devices • Actuators and pumps • Variable Speed/frequency Drives • Servomechanisms
Indoor Environmental Quality	• Smart IoT Sensors (Temperature, RH, CO, CO2 etc.)	• Environmental Quality Monitoring Platforms	• Visualization Dashboards	• Automated Control for dampers and fan speed
Security and Safety	• CCTVs • Intrusion Detection Sensors	• Security Analytics • Video Analytics	• Security and Safety Dashboards	• Automated Security and Safety Systems
Mechanical and Electrical Equipment Reliability and Uptime	• Equipment sensors (Temperature, vibration sensors)	• Reliability and Uptime Analytics	• Reliability and Uptime Dashboards	• Asset Management System monitoring real-time condition health and status
User Comfort	• Comfort Sensors • Feedback Tools	• User Satisfaction Analytics	• Comfort and User Satisfaction Dashboards	• Customer Satisfaction Monitoring System

The occurrence of intrinsic defects or issues that could result in interrupted production or subpar product quality is prevented via real-time monitoring and analytics. Machine-to-Machine (M2M) interface has made it possible to monitor condition and performance in real time through dashboards that consolidate data from all the equipment into a single source of truth.

The implementation of Industry 4.0 integrates advanced technology and affects all sectors of industry. These technologies capture, optimise, and utilise Big Data. The concept of the "Smart Factory" is gaining momentum as a vital element of Industry 4.0, according to the Boston Consulting Group [47]. IoT, AI, CPS, and cloud computing are instances of technologies that consistently establish connections, engage in interactions, and adjust accordingly. Haseltalab *et al.* [48] emphasised the increasing demand for an optimised control system through the utilisation of a Distributed Control System (DCS). The field of Information Technology (IT) science provides a range of techniques that can be utilised to optimise and enhance the execution of DCS.

The following section discusses the most widely used technologies in the scientific literature.

A. Internet-of-Things (IoT)

Ashton [49] first introduced the idea of the Internet of Things (IoT) in 1999, during the previous decades' age of wireless communications and embedded systems. We saw the emergence of IoT into smart cities, healthcare, transportation, agriculture, and other industries, in addition to the phenomenal increase in the number of sensing devices linked to the Internet.

The Internet of Things facilitates the collaboration of various computing systems, from cloud servers to sensors and smart gadgets. Conversely, the internet and mobile technology enable faraway individuals with similar experiences and ideals to interact spatially and temporally. Kobayashi *et al.* [50] suggested virtual robots, which are intelligent sensor devices placed in both the physical and virtual realms of the Internet of Things and designed to function as or on behalf of humans, have more recently brought about technological advancement. This paves the way for meaningful human-machine interaction in an Internet of Things scenario and allows physical objects to exist in a self-organized manner without a central administration [51].

B. Cyber Physical System (CPS)

NIST [52] suggested that the concept of Cyber-Physical Systems (CPS) is crucial to the execution of Industry 4.0 ideas. NIST Special Publication 1500-201 Framework for Cyber-Physical Systems: Volume 1, Overview defines cyber-physical systems as smart systems with physically and computationally constructed interconnected networks of components. The article emphasizes how these highly integrated and networked systems offer new features to enhance quality of life and facilitate technological advancements in vital fields like smart manufacturing, emergency response, traffic flow management, smart health care, homeland security, and energy supply and use. As a result, CPS provide enormous promise for enabling novel applications and having an impact on a variety of global economic sectors.

C. Cloud Computing

Using the Internet to store and retrieve files and applications rather than your computer's hard disc is known as cloud computing. The Internet can be compared to a cloud.

The German Research Centre for Artificial Intelligence (DFKI) in Kaiserslautern [53], Germany, has constructed a pilot facility that serves as a working example of a "smart" factory.

This test facility illustrates how goods and production equipment can interact with one another using soap bottles. Radio Frequency Identification (RFID) tags are affixed to empty soap bottles, and these tags tell machines whether to cap the bottles with a black or white cap. A product that is being built has radio signals that allow it to communicate with its surroundings and has a digital product memory from the start. This device turns into a cyber-physical system that allows the virtual and physical worlds to collide.

D. Cognitive Digital Twin (CDT)

Digital Twin (DT) is a fundamental enabling technology of Industry 4.0 and has been widely used to many industrial domains covering different stages of a product or system's life cycle. Integrating several pertinent DTs of a system in accordance with a defined mission is essential to properly realizing the Industry 4.0 vision. To do this, it is necessary to integrate all relevant data, knowledge, and information about the system during its whole life cycle. The increasing level of complexity of contemporary industrial systems makes it a difficult task. Potential remedies are offered by semantic technologies like knowledge graphs and ontology, which give DTs enhanced cognitive abilities. Yitman *et al.* [54] suggested a prospective progression of the current DT concept towards a more intelligent, complete, and full life cycle representation of complex systems is revealed by the recently suggested Cognitive Digital Twin (CDT) concept.

V. CONCLUSION

The volatile economic context and the rapid advances of technology are forcing industry players to adapt their economic AM models to cope with the challenges inflicted by the fierce competition of international economies. These organizations face significant uncertainties and dreaded risks of all kinds. These include the strategic, operational, organizational, and financial, as well as technological and technical issues that seriously influence all the company's business processes. Many researchers have been interested in AM models and the organizational transformation of the increasingly digitally focused business environment and its numerous tools for the development of business models to help practitioners in various industries (e.g., electrical power centers).

The new era of the industry is shaping the future of organizations and will induce profound changes in workforce planning. The digital shift is inevitably accompanied by a host of new challenges related to the connectivity of digital technologies, cybersecurity, the standardization and reengineering of business processes, the redefinition of processes, products, and services, and labor (acquisition, maintenance, and training). It brings new opportunities, new challenges, and a new organization of work.

Likewise, given the current uncertain business context caused by the COVID-19, the challenges will be of nature, among many other aspects, strategic, operational, regulatory, financial, climate change and Global warming, as well as health and safety.

In a wide variety of sectors, Integrated Risk Management (IRM) is gaining in importance. Indeed, asset managers will have to manage and operate infrastructures and utilize decision-making processes made up of panoply of complex and uncertain technological objects resulting from Industry 4.0. Furthermore, in the context of aging assets, organizations will face dependability challenges (Reliability, Availability, Maintainability and Safety—RAMS). Face with this context of aging assets, the myriad of new technologies of Industry 4.0 such as Cognitive Digital Twins (CDT), Artificial Intelligence (AI), Big Data (BD), Internet of Things (IoT), Cyber-Physical System (CPS), and cloud computing can help cope with these challenges. For instance, in electrical power industries, CDT can enhance asset breakdown detection or prediction, manage the replacement of assets when they attain their economic life span, become obsolete or when transitioning to more economical, energy efficient and zero carbon power alternatives. Also, it can strategically enable the prioritization of predictive maintenance, condition-based maintenance as well as preventive maintenance to enhance asset replacement, upgrading with sustainable measures, and optimize the resource allocation to pre-empt the probable destruction of green and smart planet.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization, C.K.H. and Y.L.S.; methodology, C.K.H. and Y.L.S.; validation, C.K.H. and Y.L.S.; formal analysis, C.K.H. and Y.L.S.; writing—original draft preparation, C.K.H. and Y.L.S., writing—review and editing, C.K.H., Y.L.S., and K.J.T. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGEMENT

The authors wished to thank C&W Services (S) Pte Ltd for the support of the project.

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