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Enhancing Reliability of Automated Handling Systems via IoT-Based Predictive Maintenance: A Regional Study

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CHAPTER 1 Introduction

1.1 General Background of the Research Field:

The advancements in Industry 4.0 have impacted the landscape of facility and asset management by revolutionizing maintenance practices, transforming traditional approaches into data-driven, intelligent operations. Facility Management (FM) works within traditional reactive protocols about asset management. IoT and BIM help a move towards proactive and predictive maintenance.

Within complex airport settings and mega-fulfillment centers, Material Handling Equipment (MHE) Figure 1-1 and Baggage Handling Systems (BHS) Figure 1-2 are indispensable for maintaining continuous material flow, traceability and sorting accuracy. IoT drives this change between sensors, controllers to a BHS or MHE through communication protocols. Combining a rich diversity of field equipment-conveyors, variable frequency drives and barcode readers with PLCs or SCADA based systems enables organization to monitor their physical assets dynamically. Anomalies can be instantly detected, downtime minimized, equipment lifespan extended. This has become a major cornerstone of smartest asset management



Figure 1-1 Material Handling Equipment system Figure 1-2 Baggage Handling Equipment system

1.2 Importance of the Topic in the Global and Local Context:

Global Importance: The global aviation industry and international supply chains are experiencing unprecedented growth in demand, as well as an increase in operational complexity and pressure to improve the quality of service while reducing costs globally; hence organisations are continuously investing heavily in the smart automation and IoT based maintenance solutions to maximise performance of critical BHS and MHE assets globally. IoT systems allow constant monitoring of assets which forms the backbone of a predictive maintenance strategy mitigating failure to the airport BHS and MHE systems. It ultimately maximises the assets' two crucial KPIs i.e. Mean Time Between Failures MTBF and Mean Time To Repair MTTR, as well as pushing its availability up to the industry standard of 99.9%.

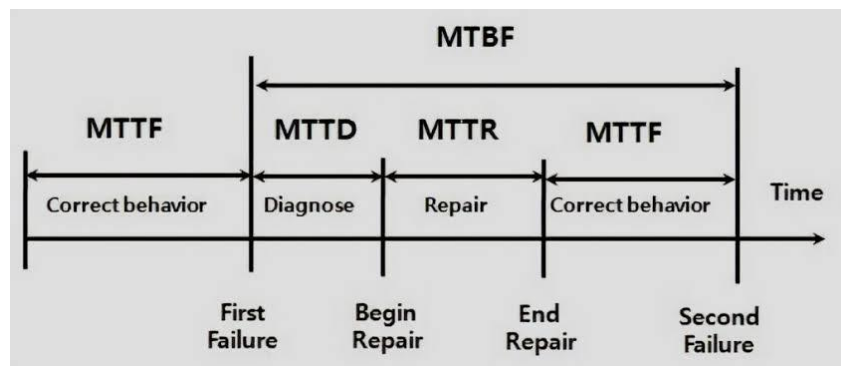


Figure 1–3 MTBF, MTTR and Availability Differences

$$MTBF = \frac{\text{Total Operating Time}}{\text{Number of Failures}}$$

$$MTTR = \frac{\text{Total Repair Time}}{\text{Number of Repairs}}$$

$$\text{Availability} = \frac{MTBF}{MTBF + MTTR}$$

Local Importance: While undergoing unprecedented modernisation in Kingdom of Saudi Arabia in accordance with Saudi Vision 2023, the Saudi aviation and logistics sector is rapidly undergoing digital transformation to improve its infrastructure and logistics abilities i.e. smart airport and cognitive city projects in which the monitoring solutions would be resilient and of quality. IoT based BHS and MHE systems are capable of maximising the operational reliability through predictive maintenance. As the Kingdom moves toward building and developing an integrated ecosystem of intelligent infrastructure and services, an IoT based predictive maintenance will help this transformation too.

1.3 Research Gap:

Although significant research has been conducted on the IoT application in general use smart buildings and IT environments much less studies are produced of IoT implementation into the real high-throughput BHS and MHE architectures. It is a focus on theoretical technological capabilities in most scientific works while little empirical analysis of exact layer (field level, sensors and route logic) integration in legacy and modern sorting facilities.

Moreover there is a lack of research about the IoT generated data which can be used through mathematical and practical way to improve hard reliability indices (MTBF, MTTR and Availability) in particular facility in specific situation. This reveals an urgent need of the applicable framework which could integrate the IoT technologies with maintenance management strategies within the specific demand of the heavy sort systems.

1.4 Overview of the Research:

The research will examine the transition to IoT-driven Facility Management, specifically in the monitoring and maintenance of Baggage Handling Systems (BHS) & Material Handling Equipment (MHE). How real-time data informs of predictive maintenance and enhanced asset performance management.

It will analyze existing sensor and PLC technology, SCADA, Automated sorting equipment and measurable impact on reliability to meet the needs of the assignment. The approach is the mixed method between qualitative by interviewing targeted 10-15 professionals and conducting a survey to 100-150 relative and potential interviewees based on secondary data research planned on the second quarter of 2026. The target area of research is mainly the major industrial/aviation hubs across Riyadh, Jeddah, Dammam & Cairo (Kingdom and Egypt). It will then present recommendations that might improve the reliability of the system, develop smart infrastructure that will be reliable in the coming years.

CHAPTER 2

Problem Statement

2.1 Research Problem:

Baggage Handling Systems (BHS) and Material Handling Equipment (MHE) are the workhorses of airports and distribution centres; forever sorting, transporting and tracking some physical asset. This equipment is critical to operations; if any component breaks, it cascades and negatively impacts facility performance, airline operations and customer-supply chain commitments. This has a disastrous financial and operational impact on the airport/distribution centre. For example, mishandled bags and delays due to mechanical failure account for billions of lost revenue each year globally in the aviation industry [the annual SITA Baggage IT Insights provides industry data]; and it is estimated that one minute of time of the down time of cross belt sorter can cost thousands of dollars in automated logistics. (Costa, 2024)



Figure 2–1 SITA interface

While physical automation level is high in these environments, Facility Management (FM) practices frequently remain traditional and reactive. Field Level control systems such as Programmable Logic Controllers (PLCs) or standard SCADA systems, are built for operational routing than preventive monitoring of equipment/asset health. And as the Saudi Vision 2030 unfolds towards the massive construction of logistics hubs and aviation mega-projects, use of traditional methods of maintenance may no longer remain feasible. Extensive work showing how to integrate various technologies belonging to the ambit of IoT has been done; still limited research is out there discussing how practical IoT technology can seamlessly integrate with the BHS and MHE architectures that currently dominate the market and are the norm for the legacy installations? Hence, why this study explore how IoT driven

Facility Management be integrated to maintenance operations can improve maintenance operations, asset performance and the system reliability of Automated Sorting environments.

2.2 Research Questions

With an aim to investigate the research problem properly, I hereby will try to provide some answers of the following questions from the literature so far, as below:

- What are the challenges, manual inefficiency and maintenance issue with operated old and traditional and old and MHE BHS system than the new ones based an IoT?
- How do MTTR, MTBF and Overall System availability relate/are altered by implementing IoT condition-monitoring?
- How IoT Integration will elevate the scope further of facility management like Energy Management and increase Asset lifecycle and enhance sustainability of the building?
- How does an IoT architecture help address technical barriers (interoperability, cybersecurity, legacy systems retrofitment), organisational barriers (management resistance to sharing data, high investments due to the high regulatory regime) and financial barriers (time-to-ROI for brownfield vs. greenfield projects) for the local aviation and logistics hub?
- What can be a proposed framework to integrate modern IoT sensors with the archaic PLCs and SCADA systems so as to perform data driven predictive maintenance?

2.3 Gap Between the Current Situation and the Desired State:

2.3.1 Current Situation:

- Maintenance depends largely on the preventive nature of maintenance or on operation to failure.
- At sub-station level, the control systems are not designed for in depth, predictive monitoring of the health of critical equipment, detection of equipment deterioration e.g. vibration of motors, operation of control sensors often occur only after a problem has caused disruption of operations.
- Performance of the buildings and equipments is collected manual and analyzed inefficiently.

- The IoT sensors need to be economically and feasibly connected to legacy building systems that are the prevalent systems installed today.
- Unexpected outage events constantly threaten to create a bottleneck in the baggage flow and decrease efficiency and customer satisfaction.

2.3.2 Desired Situation:

- IoT devices and smart sensors monitor Critical BHS & MHE assets - 24/7 visibility with data collected 24/7.
- No longer are repairs "re-active", after breaks occur; but "pre-active, seeking potential breaks prior to the actually occurring.
- Real-time operational data drastically reduces the MTTR as it continuously maximise the MTBF and pushes the Available system towards to the strict threshold of 99.9%.
- Resource usage and energy consumption is automatically and optimising it with intelligent systems.

Access to accurate, integrated data enables facilities managers to enhance the financial and environmental sustainability of their buildings, extend the lifespan of their assets and deliver on the promise of operational reliability.

2.3.3 The Gap:

The problem is the significant gap between reactive, compartmented FM practices today vs. a smart, data-driven environment with IoT. Bridging what is feasible today technologically in the world with the practical ability related to people, organizational and technical ability to upgrade legacy BHS and MHE infrastructures to enable predictable maintenance.

2.4 Evidence of the Problem

The problem is the significant gap between reactive, compartmented FM practices today vs. a smart, data-driven environment with IoT. Bridging what is feasible today technologically in the world with the practical ability related to people, organizational and technical ability to upgrade legacy BHS and MHE infrastructures to enable predictable maintenance:

2.4.1 Academic Evidence:

- Significant gaps were found in the integration of IoT with FM from literature while more practical implementation would be appreciated. (Mannino, et al., 2021)
- Challenges for organisations in the technical integration, interoperability and implementation although IoT can benefit organisations in terms of their facility management needs and requirements greatly as per (Altohami, et al., 2021).
- For the performance of airport baggage handling systems, the reliability of conveyor systems and the maintenance effectiveness turn out to be key drivers and (Koenig, 2021) recommended condition-based maintenance methods.
- Results presented by a 2022 study by Sidek et al. show that there is often a gap between expected outcomes from IoT based services and their subsequent results once in place in a public-sector organization. (Sidek, et al., 2022).
- facility managers still struggle with data management, cybersecurity and use of information generated by IoT (Olimat, et al., 2023).
- Moreover, (Gupta, 2023) demonstrates IoT implementation leading to improved failure prediction accuracy, decreased unanticipated incidents, plus the use of IoT to deploy predictive maintenance to enhance the maintenance of the baggage handler conveyor system in operation with one incident reported in previous studies but with effective use of the developed model to help identify the flaws and fix them.
- IoT-supported predictive maintenance leading to improved reliability, the reduced disruptions in the operation and the maintenance practices in smart maintenance for aviation with the maintenance practices that also make impact in the aviation related systems was highlighted by (Wong, 2023).

- Study presented by (Hebala, 2024) showed that incorporating IoT tech into smart baggage systems improves how equipment is monitored, how faults are found and overall operational productivity.
- (Hassanain, 2025) argues that inconvenience would emerge if the facility manager integrates IoT technology in his efforts to practice a sustainable facility management by creating smart building facilities.

2.4.2 Industry & Statistical Evidence:

- **Rising Maintenance Expenses:** Based on industry figures, reacting to breakdowns instead of anticipating them can lead to a 40% increase in expenses, demonstrating the financial burden that lingers with non-IoT enabled infrastructure. (Haarman, 2017)
- **The Uncaptured Potential:** Traditional facilities are currently missing out on substantial energy savings. Research by the Pacific Northwest National Laboratory (PNNL) found out that well deployed smart building controls are up for around 29% for smart savings; this means significant amount of energy saving. (Fernandez, 2017)
- **Logistics Financial Losses:** Loss minutes per system breakdown can cost up to 10k of dollars in autonomous MHE based upon a research report, resulting in the halt of the entire outbound processes when key sorters in MHE break down. (Senseye2022 ‘)
- **Significant Energy Loss:** Noteworthy the typical commercial building in U.S misuses about than 30% of its energy says the Environmental Protection Agency because of incompetency lack of tracking. (U.S. Environmental Protection Agency (EPA), 2023)
- **Aviation Downtime Impact:** Baggage handling- a cost of multibillion dollars by the aviation industry annually with many of them resulting to the misplace of luggage due to the breakdown of BH and the maintenance of their related parts after SITA Baggage IT Reports showed evidence to corroborate these facts that led to these losses caused with the Baggage handling .(SITA, 2023)

According to all recent industry reports and smart building studies, though the adoption of IoT is growing across the globe, it is held off by serious concerns related to data privacy, huge implementation costs, scarcity of skilled personnel, lack of compatibility across all the systems used by an organisation,

retrofitting legacy sorting machinery and much more! All these imply that even though the potentials IoT has to offer look lucrative for any organisations' Facility Management, there exist some serious issues in reaping those advantages and they need more than just superficial research.

CHAPTER 3

Significance of Study

3.1 Scientific Significance:

The study offers scientific significance by adding to the body of knowledge around the application IoT on Facility Management (FM) and mission critical operations such as airports, whereby Industry 4.0 and digital transformation are revolutionizing building operations and maintenance such as Baggage handling systems (BHS) & material handling equipment's (MHE) and enhancing equipment reliability, efficiency and sustainability, providing insights into its uses.

1. **Enriching Theoretical Knowledge:** This study expands on the current literature by adding to its wealth of theoretical understanding in the area of IoT based facility management, Smart Building Predictive maintenance, Smart asset management to aviation and logistics environment. It allows a deeper theoretical understanding of how disruptive technologies are reshaping the notion of traditional FM from reactive models to proactive, data-driven ecosystems and also highlights IoT and emerging BHS/MHE maintenance practice relationship in a clearer view providing a comprehensive IoT based understanding.
2. **Filling a Gap in Literature:** While similar studies have been conducted on the IoT for smart building applications in general and for facility management, literature lacks to deal with the practical deployment challenges experienced by heavy-throughput critical-systems as airport baggage handling systems (BHS) and material handling equipment (MHE). Challenges experienced in retrofitting such legacy building infrastructure/sorting systems with modern IoT technologies in local & developing context is a heavily underdeveloped stream of research. The research fills up the lacuna present by studying the relationship between the IoT-enabled monitoring system and the direct impact it has on the crucial building facilities that airport infrastructure depends on for operational performance, namely material conveyer and parcel sorting systems used for airport Baggage Handling.

3. **Providing an Integrated Theoretical Framework:** This study has delivered an integrated framework conceptualizing the role of IoT solutions in improving the areas of maintenance management, asset monitoring, smart energy and operational performance and so bridged existing gap in academic research. On top of it, this framework linking particular IoT capabilities such as predictive analytics, real-time condition monitoring tools with performance outcome will definitely become a foundation for further academic research in this field of study. The study provides an integrated framework that conceptualizes the role of IoT solutions in facility management through studying their influences on maintenance management, asset monitoring, smart energy and operational performance. This framework on specific IoT capabilities and its influence to performance leads to a foundation for future academic research in this field of study.

3.2 Practical Significance:

In addition to its academic contribution, this study have provided important benefits to practitioners such as facility managers, airport operator, maintenances. And also to policy makes and managers of an organization which deal with the management of BHS and MEH assests.

1. **Providing Recommendations for Organizations:** The conclusion from this study can help organizations understand the benefits and implementation of Internet of Things in the field of facility management. Hence the study provides recommendations resulting from the evidence, which will help organizations in their successful adoption of predictive maintenance strategies, as well as smart asset management. This knowledge will assist decision makers of critical operational systems monitor equipment better, reduce unplanned downtimes, trim down the maintenance costs, improve service delivery quality, find out the ROI that is needed to justify an initial expenditure of an financial transition.
2. **Supporting Policymakers and Decision-Makers:** It helps support the policymakers, authorities, airport management and decision-makers in providing the correct policies, regulations and implementation plans that embrace the smart FM system inside airport vital infrastructure. And the results greatly support national endeavors in smart cities, sustainability and development of tech, as the output of this project links directly to national ambitions that include Saudi Vision 2030 and cognitive development for gigaprojects such as the Line and Oxagon.
3. **Developing Measurement and Evaluation Tools:** The study stresses the importance of using particular operational KPIs to measure and evaluate performance. Tools like MTBF, MTTR

and Availability are being built to ensure the study's impact is tangible. They will assist organizations in judging their readiness for IoT integration, asset reliability, energy-saving targets and continuous development practices for improving BHS and MHE maintenance.

4. Enhancing Sustainable Facility Management Practices: IoT technology promotes data-driven decisions that can be used to improve resource, conserve and effectively maintain assets. Which can increase the level operational reliability offered to the airports the logistic infrastructure, but would further to deliver local and global targets for CO2 reduction.

CHAPTER 4

Study Objectives

4.1 General Objective

This research seeks to explore the IoT's transformative potential concerning conventional facility management, converting into smart and sustainable ecosystems, whilst assessing IoT's footprint on enhanced monitoring, maintenance, operational dependability and predictive capacities of Baggage Handling Systems (BHS) and Material Handling Equipment (MHE) across Saudi Arabi and Egypt's aviation and logistics domain as well to craft a transitional approach.

4.2 Specific Objectives

- Identify Systems and IoT Applications: Identify the main operational components of modern BHS and MHE environments and how these environments use the Internet of Things technologies (e.g., smart sensors, automated controls, PLCs, SCADA and data analytics) within these facilities.
- Analyze Historical Data: Review historical data on maintenance and breakdowns for the selected BHS and/or MHE (Operational Period 2021-2026) to define the current baselines of their reliability, noting the obvious opportunities that would be derived from the use of IoT for PdM.

- **Examine the Shift to Predictive Maintenance:** To examine how IoT-enabled real-time condition monitoring shifts traditional reactive ("run-to-failure") maintenance approaches move towards proactive and predictive methods, thereby minimizing equipment malfunctions and unscheduled operational delays.
- **Evaluate Impact on Reliability Metrics (KPIs):** MTBF, MTTR, availability: To rigorously measure and quantify the actual impact of the IoT integration on these key indicators measuring reliability.
- **Assess Sustainability and Broader FM Goals:** Wider sustainability, extending asset life, optimizing resources and minimizing carbon footprint, aligning with national strategies including Saudi Vision 2030, enhancing energy efficiency.
- **Identify Implementation Barriers:** technical, organizational, cyber-security and financial challenges to adoption, including the particular difficulties encountered in retro-fitting old baggage/material handling infrastructures and ROI justification of IoT solutions.
- **Develop an Integrated Framework:** To design an all-inclusive conceptual framework and a set of actionable recommendations to assist Facility Managers, airports operator and policymakers in successfully integrating IoT technologies for efficient smart asset management to encourage the continuous operational improvement.

CHAPTER 5

Research Questions

Specific and main questions, derived from the study's objectives, are as follows:

Main Research Question: " How can IoT provide an improvement to operational reliability, predicting maintenance in the automated Baggage Handling systems (BHS) and Material Handling equipment (MHE) and ultimately sustainability, in a facility management role? ".

Specific Research Questions: The following are some specific questions developed aimed at answering directly the core problem:

1. Existing Obstacles and Past Information: What are the primary difficulties in their day-to-day operation, servicing and dependable functioning for baggage handling systems (BHS) and material handling equipment (MHE) within airports? Moreover, when we look at how these systems have been maintained historically, what insights do those records provide about the shortcomings of the older, reactive or "run-to-failure" approaches common in facilities management?
2. IoT Applications & Technologies: What IoT applications and technologies (e.g., smart sensors, automated controls, PLCs, SCADA systems and data analytics) can be utilized to support real-time condition monitoring and continuous fault detection in BHS and MHE assets?
3. Impact on Reliability KPIs: How exactly does integration of IoT based predictive maintenance affect key maintenance and reliability metrics, Mean Time Between Failures MTBF Mean Time To Repair MTTR system availability and minimizing unexpected interruptions to operations?
4. Sustainability & Operational Benefits: To what extent does IoT-based facility management contribute to operational effectiveness, energy efficiency, carbon footprint and ROI?
5. Implementation Barriers: What are challenges that need to be prioritized and focused when moving forward to IoT in Facility Manage, in respect if legacy BHS/MHE Infrastructure (technically, organizationally, financial and cybersecurity challenges)?
6. Strategic Alignment & Readiness: To what extent are local organizations preparing to adopt Internet of Things (IoT) technologies in their facilities management practices in line with rapid regional urban developments and national initiatives such as Saudi Vision 2030?
7. Data Utilization: How can you use operation data gathered from IoT devices seamlessly integrated into the facility to inform better maintenance decision-making, while advocating and ushering in a smarter, data-driven approach to facility management?

8. Framework & Best Practices: What comprehensive strategic framework and practical recommendations can be proposed to successfully integrate IoT-based predictive maintenance and reliability management practices Figure 5-1 into both new developments and existing infrastructure?



Figure 5-1 Predictive Maintenance And Reliability Management

CHAPTER 6

Research Hypotheses

To analyse the impact of IoT implementation on facility management and dedicated sorting operations, hypotheses have been designed for quantitative evaluation. These hypotheses comprise a Null Hypothesis and an Alternative Hypothesis along with the significance factor (*e.g.*, $\alpha \leq 0.05$). as hypotheses aimed toward statistical analysis of the impacts between technological application of BHS and MHE and how it affects the operation.

Main Hypothesis:

- H_1 (Alternative Hypothesis): Implementation of Internet of Things would have a statically significant positive effect on the transformation of the facility management practices, thus improving maintenance performance, operational reliability and effectiveness of BHS and MHE systems.
- H_0 (Null Hypothesis): The adoption of IoT does not have any statistically significant impact on the transformation of facility management practices, maintenance performance, reliability and effectiveness of BHS and MHE systems.

6.1 Specific Sub-Hypotheses

H_1 : Maintenance Performance & MTBF:

- H_{11} (Alternative): There is a statistically significant correlation that Condition Monitoring based on IoT extends Mean Time Between Failures of BHS and MHE assets and effectively results in less unplanned downtime.
- H_{01} (Null): IoT-based condition monitoring has no statistical relationship between prolong MTBF and reduce unplanned down time.

H_2 : Repair Efficiency & MTTR:

- H_{12} (Alternative): Applying the fault of real-time IoT in equipment maintenance can lessen Mean Time To Repair (MTTR) a lot when it has troubles and increase maintenance management to obtain a higher efficiency.
- H_{02} (Null): The use of real time IoT fault detection does not reduce the Mean Time To Repair (MTTR) when there is an equipment breakdown.

H_3 : System Availability:

- H_{13} (Alternative): There is a statistically significant correlation that with IoT based Predictive maintenance, the chance of higher total System Availability is also more.
- H_{03} (Null): I did not observe a statistically significant association between predictive maintenance facilitated by IoT technologies and enhancements in overall system availability.

H_4 : Asset Management & Decision-Making:

- H_{14} (Alternative): IoT links clearly and positively to better asset management, the usefulness of physical assets can be maximized and the best decisions made according to hard data
- H_{04} (Null): No statistically significant relationship was found in my study. As IoT increased then there was not an improvement in overall management of assets or the quality of decisions made.

H_5 : Energy Efficiency & Sustainability:

- H_{15} (Alternative): IoT installation on facility management is resource optimized. A large gain can be achieved through IoT installation. Installation of IoT at facility management improves the energy efficiency. Installation of IoT can improve the carbon dioxide usage.
- H_{05} (Null): integrating the Internet of Things within facility management practices yields no statistically impactful improvements concerning resource optimization, energy efficiency or overall sustainability performance.

H_6 : Implementation Barriers:

- H_{16} (Alternative): Barriers of technical, cybersecurity and financial negatively affect the organisations' readiness to retrofit legacy BHS and MHE infrastructures with modern IoT systems.
- H_{06} (Null): Technical, cybersecurity and financial risks have no relation with how adequately organisations are to deal with retrofitting legacy of infrastructures with IoT.

Qualitative Proposition:

Beyond testing quantitative hypotheses, the qualitative stage in this mixed-methods approach will study how maintenance engineers, facility supervisors and airport operations staff would conceive of advantages, organizational challenges and physical implementation of using IoT-based predictive maintenance on complex BHS and MHE systems.

CHAPTER 7

Literature Review (Previous Studies)

The literature review and the critique of prior studies of Facility Management, IoT Integration & Condition Based Predictive Maintenance approaches are presented in this chapter. Followed by a comprehensive analysis outlining prevailing methodological research trends and concluding with the articulation of the research Gap addressed by this study - using the funnel approach (general smart building and retrofitting old infrastructure to use cases in (BHS/MHE).

7.1 Theme 1: Smart Facility Management and Integration Challenges

Study 1: Jia et al. (2019)

- Reference: Jia, M., Komeily, A., Wang, Y., & Srinivasan, R. S. (2019). Adopting Internet of Things for the development of smart buildings: A review of enabling technologies and applications. *Automation in Construction*, 101, 111–126.
- Objective: Review enabling technologies of IoT in smart buildings and examine their contribution on building's intelligence and general energy management.
- Methodology: A systematic literature review examining studies on wide IoT applications in a qualitative manner analyze previous researches.
- Key Findings: IoT technologies provide enhanced monitoring, energy management and security capabilities through improved real-time data capturing.
- Critique & Relation to Current Study: While offering crucial initial insight into IoT's scope and ability, it covers all newly constructed commercial buildings and general energy management. The study ignores actual working mechanics of the complex automated / heavy duty sortation

machinery / Baggage Handling System that runs the industrial facility. It has industrial facility management as its niche. (Jia, et al., 2019)

Study 2: Altohami et al. (2021)

- Reference: Altohami, A. B. A., Haron, N. A., Alias, A. H., & Law, T. H. (2021). Investigating approaches of integrating BIM, IoT, and facility management for renovating existing buildings: A review. *Sustainability*, 13(7), 3930.
- Objective: To explore how to deploy IOTs in Facility Management for the renovation and retrofitting of existing (legacy) buildings
- Methodology: Critical qualitative review of academic literature on intersection of BIM+IoT with traditional facility management practices
- Key Findings: IoT can positively impact maintenance planning and decision-making in the case of older infrastructure; however, issues of system interoperability and high implementation costs remain important barriers
- Critique & Relation to Current Study: This study theoretically concludes that IoT has a positive effect on legacy infrastructures. Given this, the IoT benefits could theoretically be applied for improving legacy PLC and SCADA architectural in the proposed local sorting facilities. The existing study provides an interesting aspect in evaluating how the actual engineering works would be like for retrofitting legacy infrastructures with IoT. (Altohami, et al., 2021)

Study 3: Sidek et al. (2022)

- Reference: Sidek, N., Ali, N., & Alkawsi, G. (2022). An integrated success model of Internet of Things (IoT)-based services in facilities management for public sector. *Sensors*, 22(9), 3207.
- Objective: Creation of an IoT based success model suitable for services at the public sector's facility management site.
- Methodology: Creation of a theoretical model in conjugation with literature analysis and subsequent validation.
- Key Findings: Organizational readiness, technological infrastructure and user acceptance are most vital factors in the success adoption of IoT within the FM.
- Critique & Relation to Current Study: This study supports our research vision on organizational readiness, with its limits that focused on public sector only across Southeast Asia only; the study expands its boundaries to rapid Middle Eastern digital transformations (Saudi Vision 2030) directly assessing the readiness of private and semi-private aviation and logistics operators. (Sidek, et al., 2022)

Study 4: Olimat, Liu, and Abudayyeh (2023)

- Reference: Olimat, H., Liu, H., & Abudayyeh, O. (2023). Enabling technologies and recent advancements of smart facility management. *Buildings*, 13(6), 1488.
- Objective: Identify new technologies (such as IoT, AI, and digital twins) that exclusively improve smart facility management.
- Methodology: Utilizing a systematic literature review to examine recent technological innovations FM sector.
- Key Findings: Results The integration of IoT would enable companies to improve the quality of their maintenance operation, to manage their assets better & switch from reactive/proactive maintenance mode to predictive mode. However, companies still encountered the challenges in data & systems integration.
- Critique & Relation to Current Study: While the study identified technical barriers, it did not empirically investigate the financial barriers (ROI) and organization's readiness facing FM. It bridged this gap quantitatively. (Olimat, et al., 2023)

7.2 Theme 2: Predictive Maintenance and Reliability in BHS/MHE Systems

Study 5: Koenig et al. (2021)

- Reference: Koenig, F., Found, P., Kumar, M., & Rich, N. (2021). Condition-Based Maintenance for Major Airport Baggage Systems. *Journal of Manufacturing Technology Management*, 32(3), 722–742.
- Objective: The main aim of this study is to discuss how the airport can improve its baggage systems without adding new equipment and by simply changing to the CBM from reactive system, for better baggage system performance.
- Methodology: Case Study research method examining processes and conducting semi-structured, one-on-one interviewing with maintenance specialists in a 24/7 airport baggage handling system used in major airport facility in Kingdom and Egypt.
- Key Findings: Condition-based maintenance drastically improves equipment reliability, reduces maintenance costs and enhances system availability compared to traditional reactive

strategies. Reliability of the conveyor system was found to critically influence overall performance of the airport.

- Critique & Relation to Current Study: Koenig et al. proved a requirement for BHS to possess CBM-However this, being a result of only a qualitative case study lacked statistical numbers to exactly quantify an effect on the Availability of a system. Current research tests this against empirical data using a blend of statistical analysis techniques and historical data; the variables are analyzed together to prove that a correlation between CBM type has an effect on the system Availability of BHS. (Koenig, 2021)

Study 6: Wong & Man (2023)

- Reference: Wong, E. T. T., & Man, W. Y. (2023). Smart Maintenance and Human Factor Modeling for Aircraft Safety. *Springer*.
- Objective: To examine the role of smart maintenance technologies, specifically focusing on IoT-enabled condition-based monitoring systems, in improving maintenance effectiveness within the aviation environment.
- Methodology: Focuses on surveying novel techniques based on reliability to examine the developing trends of information driven maintenance.
- Key Findings: IoT-enabled predictive maintenance decreases operational disruptions, improves equipment reliability and enhances decision making capabilities.
- Critique & Relation to Current Study: This study supports the ground of research in aviation for smart maintenance, however the emphasis is on the aircrafts flying safe in addition to human factors than directly on ground-based systems It creates pre-study information to research, in which prediction work focuses solely on ground-based system MHE. (Wong, 2023)

Study 7: Gupta et al. (2023)

- Reference: Gupta, V., Mitra, R., Koenig, F., & Kumar, M. (2023). Predictive Maintenance of Baggage Handling Conveyors Using IoT. *Computers & Industrial Engineering*.
- Objective: To determine whether luggage conveyors can be effectively health-monitored using IoT-enabled sensors to predict failure before they actually happen.
- Methodology: Adopting a quantitative experimental investigation using real-time operational and maintenance data on working airport baggage handling systems.

- **Key Findings:** Results indicated that the implementation of IoT-enabled predictive maintenance strategies led to improvements in fault detection, reduction of unplanned downtime incidences and effective downtime reduction.
- **Critique & Relation to Current Study:** While offering substantial quantitative evidence for IoT-driven accuracy gains in BHS, this study focused on algorithm prediction and neglected its relation to the wider KPIs relating to facility management. Sensor capabilities used to measure the maintenance parameters of concrete (MTTR and MTBF) in the scope of Holistic Operational Management. (Gupta, 2023)

Study 8: Hebala & Ashour (2024)

- **Reference:** Hebala, A., & Ashour, H. A. (2024). Realisation of Cooperative Conveyor-AGV Smart Luggage Handling System through AI-Based Object Detection and IoT. *IEEE Conference Proceedings*.
- **Objective:** Create a smart, IoT, AI, IoT & automation driven solution to the challenges luggage transportation can create.
- **Methodology:** Experimental method of evaluating autonomous baggage handling IoT Communication model.
- **Key Findings:** Automated spaces benefited from an increased tracking accuracy; improvement in the monitoring and reaction of the environment via the equipment.
- **Critique & Relation to Current Study:** While relevant to BHS technologies, this study centered on baggage tracking and automatic detection of objects. This current research shifts the operational sight from "tracking the bag" to "tracking the health of the machine routing the bag". Mechanical reliability concern is highlighted as opposed to bag tracking accuracy (Hebala, 2024)

7.3 Comprehensive Analysis of Previous Studies

Similarities and Differences in Findings: All studies unanimously agree on the fact that IoT is the trigger for the critical change from reactive to proactive ("run-to-failure") to proactive- predictive maintenance (and more advanced) (Olimat, et al., 2023; Gupta, 2023). IoT technologies provide better MTBF, longer life of assets, reduction in downtime (and the associated opportunity cost). Again, all studies also agree on the fact that there are severe roadblocks to IoT adoption primarily

led by high costs, cybersecurity, organizational readiness and the huge technical challenge of retrofitting legacy as well as existing infrastructure (Altohami, et al., 2021; Sidek, et al., 2022).

Methodological Trends and Discrepancies: this is an area in which there is much to be achieved. All the papers focusing on FM (Jia, et al., 2019; Altohami, et al., 2021) have relied almost entirely on qualitative, secondary literature reviews. The studies focused on aviation and BHS have either relied on experimental design(isolated) (Gupta, 2023) or taken a qualitative single site case study (Koenig, 2021). There appears to be a conspicuous absence of empirical studies using a primary, mixed methods approach which involves surveying FM professionals and then concurrently studying quantitative breakdown data (MTTR/MTBF).

7.4 Research Gap Statement

From reviewing existing literature critically, five distinct strands of gap areas are highlighted below; consequently, this demonstrates the requirement of undertaking the current study:

1. Contextual and Geographical Gap: Many studies cover either the thorough developed west-east Asia markets/ therefore there is a notable gap. Empirical data is sorely needed about IoT-based BHS/MHE maintenance, especially considering the swift digital shifts and substantial cognitive advancements occurring in the Middle East, exemplified by initiatives like Saudi Vision 2030.
2. Implementation and Retrofitting Gap: IoT can provide benefits to industry at grass root level but what are the engineering challenges, financial challenges (ROI to existing plants) involved in replacing outdated/in-use field level PLCs and SCADA system.
3. Variable Integration Gap (KPI Focus): Existing literature has a common flaw as a single concept considering IoT purely within IT. Literature hardly ever correlated IoT sensor data directly to hard FM reliability indicators like MTBF, MTTR and Availability in mathematical terms.
4. Methodological Gap: too many of the studies were theoretical, many on a small experimental model or none on mixed-methods approach using historical quantitative failure data on with airport and logistic practitioners insights.
5. Scope of Focus: Focus on the routing itself. Previous research explores things like tracking accuracy and how human factors affect airport efficiency.

The IoT related adoption within a BHS/MHE hence will help the present study to fill the gaps through conducting a quantitative & qualitative research, subsequently providing a localised actionable strategy.

7.5 Analysis of Previous Studies

From reviewing the literature, some similarities and differences can be concluded in terms of what they found, which methods were used and what their attention was paid on. It is a mix of the bigger pictures of smart Facility Management and high technical requirement of Baggage Handling System and Material Handling Equipment and find the exact researching gap.

7.5.1 Agreement and Differences in Findings:

Most studies arrived at the same conclusion about the favourable impact IoT technologies might have on operational performance. Those focused on general FM (Jia, et al., 2019; Olimat, et al., 2023) agree that introduction of IoT greatly contributes towards improved maintenance efficiency, asset monitoring, better energy management and so on. Similarly, aviation and BHS focused studies (Koenig, 2021; Gupta, 2023) confirmed the drastic improvement of the equipment reliability, facilitated fault detection and minimised unexpected operational downtime related with introduction of condition based monitoring due to new IoT technologies. Altogether those papers show the critical change from reactive approach (run-to-failure) to pro-active, predictive maintenance models.

The irony though is reflected in the realities of its implementation. While, from some it is derived that the implementation is no less than managing data, others consistently draw attention to massive implementation barriers from cyber security concerns and high cost of implementation, to interoperability problems, especially noting its difficulty in legacy buildings with financial costs of sorting infrastructure and its technological hurdles (Altohami, et al., 2021; Sidek, et al., 2022) Therefore the conclusions should be seen of a complementary type highlighting both the theoretical opportunities that IoT might present with barriers to its implementation.

7.5.2 Similarities and Differences in Research Methodologies:

Research methodologies employed differed depending on the scales and aims of each study, this highlights the methodological gap:

- General FM Studies: Most studies used a qualitative, System Literature Review (SLR) approach, relying predominantly on reviewing secondary data to examine current knowledge, than empirically testing in the primary setting. (Jia, et al., 2019; Mannino, et al., 2021; Olimat, et al., 2023)
- BHS/Aviation Studies: By contrast, literature specifically on BHS tended to use standalone primary data. (Koenig, 2021) conduct research action, using single-site qualitative case studies with real-world adoption of IoT. (Gupta, 2023) instead utilized quantitative experimental designs with physical sensor data. Another study, by (Hebala, 2024), concentrated on technical system design and how to integrate AI.
- The Methodological Void: Comprehensive mixed-methods empirical research, combining large-scale surveys with historical operational logs, that directly tests these adoption variables on facility management professionals in real-world settings is notably absent.

7.5.3 Reasons for Differences in Results

Although studies generally concur on the benefits of IoT, the differences in conclusions may be attributable to four reasons, in particular for studies addressing the ease of implementation and measured outcomes:

1. Differences in Research Context and Environment: Some studies examined IoT adoptions within the context of new structures considered as smart buildings (Jia, et al., 2019). Others concentrated on the much more complex task of retrofitting older, existing infrastructure (Altohami, et al., 2021). Furthermore, general aviation environments have vastly different mechanical realities compared to the heavy, high-speed electro-mechanical requirements of BHS conveyors (Gupta, 2023).
2. The physical setting and geographic location of studies vary: Many research and studies conducted are for technologically savvy cities/countries in the Western and South-East Asia. There simply is not much research looking at the quickly developing markets found in the Middle East-specifically where massive digital overhauls are happening at an extraordinary speed,

coinciding with colossal projects such as Saudi Vision 2030. This gap in the research helps to explain why we still have such an incomplete picture of readiness within local organizations.

3. **Divergence in Research Aims and Data Origins:** Work that drew from actual maintenance logs yielded insights into downtime and reliability, matters of tangible concern (Koenig, 2021). Conversely, studies relying on literature synthesis or simulations tended toward an examination of potential advantages for IoT systems, than addressing the concrete financial and managerial hurdles
4. **Variation in Performance Metrics:** Researchers measured different KPIs. Instance, some investigations concentrated widely on energy oversight and user satisfaction. Still others were more concerned with the automation of tracking. Crucially, direct examination of core reliability figures, like the Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR) and overall system availability, was notably absent, creating a significant deficiency in the literature.

7.6 Analytical Conclusion and Research Gap Statement

Much of the writings I read agreed that IoT and predicting technology can influence and improve facility management practices. However, these documents studied IoT, Smart city or Facility management tools individually. Therefore, I researched and studied these gaps in my project:

- **Geographical and Contextual Gap:** It is an extreme scarcity of studies providing empirical evidences investigating how IoT can support FM practices within Middle Easter Countries in alignment of digital transformation initiatives in the region such as Saudi Vision 2030.
- **Implementation and Retrofitting Gap:** Studies to date have heavily underexplored the technical retrofitting of older, legacy BHS and MHE infrastructures with modern smart systems as well as the justification of a clearly defined ROI to support financial outlays.
- **Variable Integration and KPI Gap:** Most research evaluates general operational efficiency without mathematically correlating IoT sensor data directly to hard maintenance performance indicators (MTBF, MTTR and Availability) in automated baggage handling operations.
- **Methodological Gap:** Empirical research with mixed methods including stakeholder's perception and analyzing the practical implication of IoT implementation including past data.

To summarize, the study that has been discussed earlier highlights the shortcomings of current studies done on similar topic (that is on the scope of IoT and/or predictive maintenance deployment for BHS and MHE in local airport settings). Also, the article attempts and takes an approach to fill in these gaps through an approach that integrates IoT for asset monitoring, predictive maintenance and reliability performance assessment approach towards BHS & MHS while contextualizing results into our own local conditions in the course local airport. It presents a useful actionable strategic framework for effective implementation.

CHAPTER 8

Research Gap

8.1 Introduction

This thorough review and analysis of previous studies on Internet of Things (IoT) technologies and predictive maintenance indicate both the significant promise these innovations hold for altering facility management practices and that a clear "knowledge void" still exists at how IoT technologies and predictive maintenance applied at high throughput heavy electro-mechanical environment. The current research highlights the research gap in this area, that it is the first to address that is the subject of current research:

8.1.1 Limited Research Focus and Variable Integration

The previous related studies have focused on the IoT applications, predictive maintenance and condition-based monitoring as separate variables. No integrated IoT enabled condition monitoring reliability research framework for BHS/ MHE at sorting facilities was found in the literature. IoT generated data were rarely linked up with hard quantitative reliability indicators such as Mean Time Between Failures(MTBF), Mean Time To Repair (MTTR) and System Availability which are the true performance metrics at BHS. Hence, this work aims to bridge the research gap by exploring IoT as a solution tool with an integrated point of view than as a separated invention.

8.1.2 Practical Implementation and Retrofitting Challenges

Previous Past literature often discusses " theoretic " opportunities available for smart technologies, with the implied assumption that the install is being performed at a " greenfield " , New website. However there still remains a large gap about the practical engineering and cost of retrofitting IoT sensors on legacy BHS/ MHE infrastructure (which underlay all current major airports). System interoperability issues, Cybersecurity risk, Organisational resistance alongside the inability to establish a clear RoI on older assets are all largely underexplored. This provides a balance examination of these barriers, shifting the focus from the theoretical opportunities to the practical plausibility.

8.1.3 Geographical and Contextual Gap

Even though a lot of research on Smart Infrastructures has been conducted around the globe there is not a single piece of evidence on the application of IoT within the Middle Eastern Aviation and Logistics Industry. The Middle Eastern with its Mega Projects like Saudi Vision 2030 and in general Mega Projects and Building Cognitive Giga - project are getting digitized fast. There is literally no article considering the organizational readiness, technological infrastructures and local operational content of the Airports of Saudi. The study covers that part along with IoT technology to showcase the empirical evidence on the local markets operation need.

8.1.4 Methodological Gap

A significant percentage of the earlier studies relied mainly on reviews of literature, conceptual frameworks or a stand-alone simulation. A severe methodological deficiency has existed, with no one attempting a mix of quantitative and qualitative work. I hope to provide some answers using a research design (mixed approaches) that can provide:

- Quantitative validation: The empirical analysis of historical failure logs and maintenance performance metrics (MTBF, MTTR, Availability).
- Qualitative depth: By researching the perceptions, organizational readiness and challenges faced during practical application by maintenance engineers and operational supervisors.

8.2 Research Gap Statement

While researching it surfaced that we know that IoT technology could serve as the perfect smart building technology; however nobody really looked deeply into implementing it in BHSs and MHE operations specifically. There' s a big hole in the body knowledge on how to take a practical and data-based approach that deals with the complex challenges associated with modernizing legacy sorting systems and increasing reliability in today' s fast-changing environment.

This study aims to address these shortcomings. We will explore how IoT can improve BHS/MHE performance. We will also pinpoint obstacles to adoption locally. Finally, I plan to offer a practical, unified strategic framework designed for smart asset management. This framework should meet operational reliability needs and support Saudi Arabia's larger digital transformation objectives.

CHAPTER 9

Theoretical Foundations of the Study

9.1 Theoretical Framework

This research integrates multiple theoretical perspectives to explore technology adoption, the ongoing upkeep of complex assets and the digital shifts occurring within industrial sectors.

1. Technology Acceptance Model (TAM):

- Overview: Looking at how TAM is used today considering work such as (Venkatesh ‘ 2016Al-Emran2018 ‘) researchers highlight *Perceived Usefulness* (PU) and *Perceived Ease of Use* (PEOU) as the main forces behind technology adoption.
- Application: offered here demystifies why facility managers are making the switch away from reactive "run-to-failure" strategies toward prognostic, IoT-driven predictive maintenance approaches. The following will also shed a specific focus on the " Perceived Ease of Use" about the engineering challenges of IoT update of older PLC and SCADA system in Kingdom and Egypt existing plants. Older systems presented a hurdle.

2. Diffusion of Innovation (DOI) Theory:

- Overview: Recent frameworks (Tu '2018 'Dearing2018 ') analyze how technological innovations spread across industrial clusters based on *Relative Advantage*, *Compatibility*, and *Complexity*.
- Application: It analyzes why some Kingdom and Egypt's logistics organizations adopt IoT faster than others, focusing on how external catalysts like Saudi Vision 2030 accelerate adoption by highlighting the *Relative Advantage* (ROI) and addressing *Compatibility* with existing infrastructure.

3. Reliability-Centered Maintenance (RCM) Theory:

- Overview: Current RCM frameworks (Catelani, et al. '2020 'Al-Turki2019 ') focus on data-driven decisions to preserve system functionality.
- Application: It provides the mathematical basis for this study by defining the key dependent variables: Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and System Availability.

4. Industry 4.0 and Smart Asset Management Theory:

- Overview: The main Industry 4.0 literature nowadays combines IoT, real-time analytics and automated physical system (Schwab '2016 'Alcácer2019 ').
- Application: Digital transformation framework connects the physical field-level assets (BHS/MHE sensors) to have a higher level based on predictive analytics.

CHAPTER 10

Research Methodology and Methods

10.1 Justification for Mixed-Methods Approach:

A Concurrent Triangulation Mixed-Methods (Design) research method is used. Quantitative research data by itself cannot show the engineering problems and technical challenges faced while retrofitting older PLCs and SCADA systems- all of which are usually out of sight. A research solely based on qualitative interviews will not give the statistical proof one seeks to certify the effect of IoT on performance parameters like M&TB and MTTR. While both together give a deep picture of the effect of organizational preparedness on reliability from a mathematical and scientific perspective. Combining both methods gives a holistic picture, associating preparedness to technical challenges(qualitative methods) with statistical data (quantitative methods) showing the effect of such preparedness(or unpreparedness) on System reliability.

10.2 Research Type:

The research conducted here falls under the umbrellas of descriptive, explanatory and applied studies:

- Descriptive Research: The research will describe the current status of the adoption of IoT technology in BHS and MHE context and try to capture the highlights which are regarded as the key advantages as well as key difficulties were encountered in operation.
- Explanatory Research: Explaining the relationship of cause and effect in the IoT adoption (independent variable) and maintenance performance indicators (dependent variables). Testing the hypotheses formed strictly, Explaining the Cause & Effect relationship of the IoT application which, acts as the (independent variable) and the maintenance related performance indicators (dependent variables) which. Testing and strictly confirming/refuting the formed hypotheses through this method.
- Applied Research: It proposes a set of Practical and Actionable recommendations to organizations in Riyadh and a strategic framework to improve facility management through IoT, in line with Saudi Vision 2030's push for digital transformation.

10.3 Research Approach

A Mixed Methods Approach (Explanatory Sequential Design) is used to explore both measurable impacts and the various and difficult barriers in the organization. It uses triangulation- quantitative and qualitative approaches, both supporting the work, making it valid and reliable:

- **The Quantitative Phase:** I will proceed to a structured questionnaire. Participants will be maintenance engineers, BHS supervisors and operations staff from twelve selected organizations. The main goal here is to statistically assess how IoT adoption influences reliability metrics like MTBF, MTTR and Availability. We will also look at overall operational performance. SPSS will be employed for all statistical analyses.
- **The Qualitative Phase:** After the survey is completed, semi-structured, in-depth interviews are carried out with maintenance executives and automation experts. In this stage the why is and how is of the statistical results will be answered, with attention to engineering complexities about upgrading legacy PLCs, cybersecurity risks and organizational challenges encountered the companies that will have filled the survey out.

10.4 Research Design

The study selected a **cross-sectional design** for the quantitative phase as the intent was to do a one-time data collection snapshot of the current state of operational maturity with follow up of expert interviews for context, depth, strategic meaning.

10.5 Research Procedures and Implementation Plan

The research is to be worked through according to the following stages:

- **Stage 1:** Literature Review & Theoretical Grounding: Review Literature after 2016 to find gaps, build TAM & DOI to build the base framework.
- **Stage 2:** Instrument Development:
 - *Quantitative Tool:* Designing a five-point Likert scale questionnaire to measure IoT adoption levels and maintenance KPIs

- *Qualitative Tool:* Developing an interview guide tailored to explore retrofitting barriers, ROI metrics, and legacy infrastructure integration.
- **Stage 3:** Quantitative Data Collection & Analysis: Distributing the survey to technical personnel in the 12 selected Riyadh based organizations. Data will be analyzed using **SPSS** through Descriptive Statistics, Reliability Analysis (Cronbach's Alpha), Correlation and Regression Analysis.
- **Stage 4:** Qualitative Data Collection & Analysis: A-depth interviews with selected expert. (Will use **Thematic Analysis** to search for re-occurring themes/challenges/solutions)
- **Stage 5:** Integration and Strategic Framework Development: Triangulating the quantitative and qualitative findings to propose a localized, actionable strategic framework for IoT-based predictive maintenance in BHS and MHE environments, validated against Saudi Vision 2030 objectives.

CHAPTER 11

Study Instruments

11.1 Introduction:

For this research study, the researchers used a mix method Figure 11-1 approach choosing two main data collection instruments: semi-structured interview guide and structured questionnaire are used to achieve the research objectives.

11.1.1 Semi-Structured Interview Guide

Purpose: The interview guide delves beyond the surveys, uncovering experts' views & experiences of IoT, practical benefits, hidden challenges and future opportunities which are crucial for success in the FM sector.

Target Participants: It serves Maintenance Engineers, Smart Building Specialists, IoT Technology Experts, Facility Managers and IT/Operations Directors, Automation Engineer, covering Riyadh, Dammam and Cairo.

Structure: The guide with 10-12 open-ended questions will concentrate of 4 themes:

Current Adoption Status: What is the current level of adoption of IoT technologies in a facility's operations? (e.g. smart sensors, automated controls)

1. Perceived Benefits: IoT's effect on efficiency in maintenance. - Traditional reactive transformed to prediction-based model. - Energy management. - Data based decision of taking actions.
2. Implementation Challenges: Engineering difficulties retrofitting old plant, cyber security issues for old plant, lack of required skill, Hard to define clear ROI.
3. Future Opportunities: Future expected developments of IOT in context with Saudi Vision 2030 and future trends. (Suggestions by experts on how to successfully carry out IOT in Saudi context).

Structured Questionnaire:

Purpose: To gather quantitative data to investigate whether the use of IoT - an independent variable affects facility management performance which acts as the dependent variables.

Measurement Scale: A standard five-point Likert scale was employed. This scale ranges from 1, representing Strongly Disagree, to 5, signifying Strongly Agree.

Questionnaire Sections:

- Part One (Demographics): Gender, age, educational qualification, job position, years of experience, organization type and facility type (New vs. Legacy).
- Part Two (IoT Adoption Readiness): [10 Items] This section assesses IoT readiness by examining sensor installation, how data streams in real-time and how well it integrates with current systems. This approach is based on DOI Theory. *It is important to gauge these factors.
- Part Three (Maintenance Management Efficiency): [8 Items] Assessing progress on changing to prediction-based maintenance from preventative; decreasing number of hours of unplanned breakdown (downtime).
- Part Four (Energy & Sustainability Performance): [8 Items] This section measures reductions in energy use, how efficiently resources are being utilized and whether the project aligns with its sustainability goals.
- Part Five (Operational Performance): [8 Items] It will investigate aspects such as the comprehensive evaluation of service quality, the alacrity of decision-making processes involved and the ultimate financial return on investment observed over an extended period.

11.2 Instrument Development and Validation

11.2.1 Instrument Development

The items could be selected on:

- Aims and hypotheses of research
- A systematic look into research between 2016-2026.
- The theoretical constructs derived from the Diffusion of innovation theory (DOI) & the Theory of Acceptance Model (TAM).

11.2.2 Validity Testing (Expert Validation)

A selection of interview questionnaires will be reviewed by a panel of professors and industry professionals for content and face validity. The experts will provide feedback on:

- Clarity: Using professional language and making it unambiguous.
- Relevance: Each item relates directly to the objectives.
- Completeness: Checking IoT, Performance, ROI and Retrofitting that all necessary critical variables have been included. All these elements will be changed once everyone have agreed to them prior going to the field.

11.2.3 Reliability Testing (Internal Consistency)

- Pilot Study: Before distribution a small sample of the target group would be requested to review (15-20 respondents) to ensure questions make sense and do not create any ambiguities.
- Cronbach's Alpha Coefficient: Reliability SPSS will be used for reliability testing. The cut off is ≥ 0.70 for internal consistency. Acceptable level: 0.70 – 0.79 Good level: 0.80 – 0.89 Excellent level: 0.90 +. Any construct which is beyond the limit of 0.70 will be subjected to the rigorous revision of its items prior to the final collection of data.

Table 11–1 Cronbach's Alpha Interpretation Scale

Cronbach's Alpha Value	Reliability Level
≥ 0.90	Excellent
0.80 – 0.89	Good
0.70 – 0.79	Acceptable
< 0.70	Requires Revision

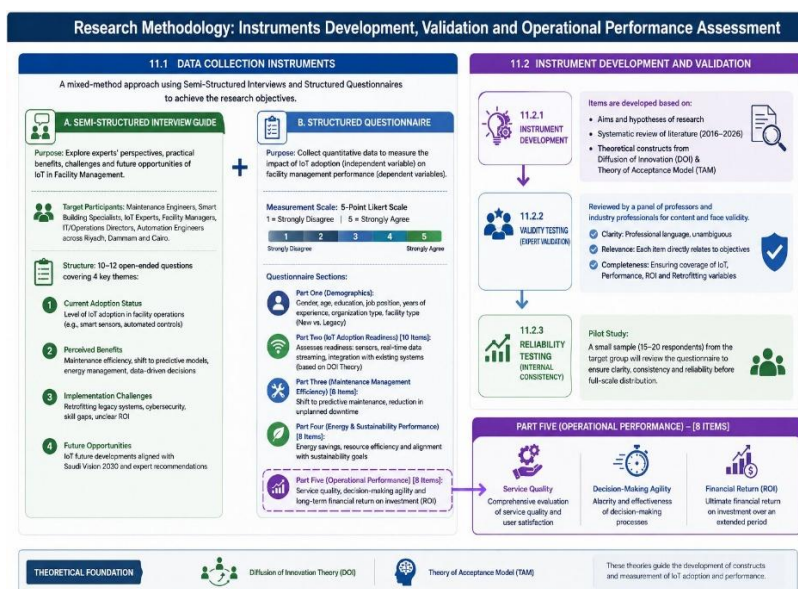


Figure 11–1 Research Methodology Mixed Framework

CHAPTER 12

Study Delimitations

12.1 Introduction

It presents boundaries within which this research project will be undertaken thus enabling it to be focused, manageable and to remain relevant.

12.1.1 Human Scope

- Study Population: Professionals from Baggage Handling Systems (BHS) and Material Handling Equipment (MHE) operation, development and maintenance including, the target population are professionals who are associated with BHS/MHE industry, with either operation, development or maintenance divisions, such as;
 - Maintenance and Automation Engineers.
 - BHS and MHE Supervisors.
 - Operations Directors and Reliability Specialists.
 - IT and IoT Systems Architects.
- Study Sample: A census approach by using purposive sampling method was conducted. There were in total 12 companies in the aviation and logistics industries involved. A census approach by using purposive sampling method was conducted. This group included well-known entities like Riyadh Airports, Amazon, FedEx, Aramex, SAL, UPS, SPL, Naqel, DHL and also major airport operators. All of them were part of our selection.
- Sample Size:
 - Qualitative Phase: 12-15 in-depth interviews with subject matter experts (one to two experts per organization) to capture deep operational insights.
 - Quantitative Phase: A target of 100-150 survey respondents across technical and maintenance departments within the 12 selected organizations to ensure statistically significant data.

12.1.2 Spatial Scope

The study takes the multi-site international scope which deals with the major logistics & aviation hubs within:

- Saudi Arabia: Riyadh, Jeddah and Dammam (due to their role in the region's logistic hub and acceleration of Saudi's 2030 vision projects).
- Egypt: Cairo (major regional aviation and logistics gateway with differing modus operandi).
- Justification: Such a distribution will aid in a comparative analysis of IoT adoption practices among these ME countries along the logistics corridor with varying degree of regulations, infrastructure, tech adoption.

12.1.3 Temporal Scope

- Study Period: The scope of study will cover developments, practices and literature in Io, predictive maintenance and smart infrastructure published from the years **2016 -2026** to identify the fast changes going in the world of 4.0 revolution.
- Data Collection Period: The time of gathering my information is between April 2026 and September 2026. This entails second and third quarters of the year. I shall have six months over which to gather primary fieldwork in form of interviews, surveys but also look up archival maintenance logs for information in mean time between failures and mean time to repair statistics.
- Performance Data Range: The reliability data includes historical breakdown data and performance logs from the last 5 years from **2021 to 2026** from which the trends have been identified.

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