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"Asset MAnagement in the new Digital Twins environment" (AMADIT)

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1. INTRODUCTION

1.1. Background

With the advent of digital technologies, maintenance management is transforming into a predictive and data-driven process that enhances decision-making and resource allocation at all three levels of maintenance activities: strategic, process, and operational. While much of the focus has been on operational improvements, such as real-time monitoring and predictive maintenance, the impact of digitalization extends to higher-level strategic decisions as well.

- *Operational Level:* Digitalization directly addresses operational issues by integrating technologies like IoT, AI, and Digital Twins to monitor asset conditions in real time. This allows for predictive maintenance, minimizing unplanned downtime and improving overall asset reliability. IoT sensors collect vast amounts of operational data, which is analyzed to identify patterns that indicate potential failures. Maintenance tasks can then be scheduled based on actual asset conditions, reducing unnecessary maintenance activities and optimizing resource use.
- *Process Level:* At the process level, digitalization enhances workflow optimization by integrating maintenance management software (e.g., EAM systems) with real-time data. It supports the automation of maintenance schedules, resource allocation, and inventory management, streamlining processes and improving efficiency. Additionally, data analytics provide insights into process performance, helping organizations identify bottlenecks, reduce inefficiencies, and improve coordination across teams and departments.
- *Strategic Level:* Digitalization offers substantial benefits at the strategic level, where higher-level decisions regarding asset management, reinvestment planning, and long-term maintenance strategies are made. For instance, digital tools can support criticality analysis by providing comprehensive data on asset performance, failure rates, and operational importance. This allows organizations to prioritize assets for reinvestment or targeted maintenance efforts. Additionally, maintenance and reinvestment planning can be enhanced through predictive analytics, which use historical and real-time data to forecast future maintenance needs, optimize budgets, and ensure the long-term sustainability of assets. This strategic alignment helps decision-makers plan for asset upgrades, resource allocation, and risk mitigation over extended periods.

By integrating digital tools at all levels of maintenance activities, organizations can reach a proactive management, ensuring that both short-term operational issues and long-term strategic objectives are addressed efficiently.

1.2. Objectives and Scope of the Document

The objective of this document is to provide a comprehensive guide on how to digitalize assets and maintenance management processes and to identify the frameworks that support these digital transformations. Digitalization is not only about enhancing existing processes but also about enabling new and innovative ways of managing maintenance through advanced technologies. The key goals include:

- Offering actionable steps for implementing digital maintenance processes.
- Identifying relevant frameworks and standards that facilitate digital integration in maintenance.
- Addressing common challenges and providing strategies for overcoming them.
- Highlighting the role of sustainability in digital maintenance practices.
- Exploring emerging processes that digitalization may bring to maintenance management. For instance, AI-powered systems, smart scheduling and resource allocation, the integration of collaborative platforms and augmented reality, etc.

The scope of this document focuses on:

- How digital technologies such as IoT, AI/ML, and digital twins can be used to enhance maintenance management processes.
- The critical importance of integrating advanced digital frameworks into the maintenance process.
- Practical recommendations for aligning digitalization with organizational objectives and improving maintenance outcomes.

1.3. Importance of Frameworks in Supporting Digitalization

Frameworks play an essential role in streamlining digital maintenance processes by ensuring consistent data flows, enabling effective decision-making, and providing organizations with a clear roadmap for scaling their digitalization efforts. They act as the backbone for aligning maintenance practices with broader organizational goals, including regulatory compliance, sustainability targets, and long-term asset management strategies. Without the support of well-defined frameworks, the integration of advanced technologies can become fragmented, leading to inefficiencies such as data silos, limited interoperability between systems, and missed opportunities for leveraging insights across the organization. Moreover, frameworks provide a standardized approach to digital maintenance that is necessary for ensuring that processes are scalable and adaptable. They allow for the seamless integration of real-time data from multiple sources, which is crucial for making informed, data-driven decisions in maintenance management. As organizations move through their digital transformation journey, having a structured approach becomes even more critical, as it helps maintain clarity and continuity in the deployment and management of digital systems.

In this context, understanding the structure and rationale behind these frameworks is vital. They not only ensure that digital maintenance processes are consistent and reliable, but also enable organizations to respond proactively to challenges, optimize operational performance, and create a future-proof system.

As we explored how to digitalize assets and improve maintenance processes, we have identified practical, well-supported recommendations that are both innovative and rooted in industry best practices.

Table 1 outlines a range of key frameworks and standards that support asset digitalization across various industries. While not exhaustive, this selection highlights widely recognized methodologies that provide structured approaches for managing the lifecycle, data integration, and operational performance of assets. These frameworks act as foundational tools, enabling organizations to navigate the complexities of digital transformation while maintaining alignment with their strategic objectives and ensuring sustainability in the long run.

Category	Framework/Standard	Sector	Description
General Enterprise/Architecture Frameworks	**The Open Group Architecture Framework (TOGAF)**	IT, Enterprise Architecture	The Open Group Architecture Framework (TOGAF) is a framework for enterprise architecture, helping organizations align IT strategies with business goals.
	ISO 55000: Asset Management – Management Systems	Cross-industry	ISO 55000 focuses on asset management systems, offering a framework for managing physical assets over their life cycles.
	ISO/IEC/IEEE 42010: Systems and Software Eng. - Architecture Description	IT, Systems Engineering	ISO/IEC/IEEE 42010 provides guidelines for the architecture description of systems, ensuring consistency in system design and management.
Industry-Specific Frameworks	ISO 15926-13:2018: Industrial automation systems and integration	Cross-industry	Integration of life-cycle data for process plants including oil and gas production facilities.
	Building Information Modeling (BIM). ISO 19650	Construction, Architecture, AEC	Building Information Modeling (BIM) integrates 3D modeling with digital databases to support all phases of construction and facility management.
	Common Information Model (CIM). IEC 61970-301:2020	Energy, Utilities	Common Information Model (CIM) standardizes the representation of network data for utilities, especially in the energy sector.
	Product Lifecycle Management (PLM). ISO 10303 (STEP)	Manufacturing, Aerospace	Product Lifecycle Management (PLM) manages a product's lifecycle from inception through engineering design and manufacturing to service and disposal.
	UIC Reference Framework	Railway infrastructure	Utilized in the railway industry to guide digitalization efforts in maintenance and AM, promoting sustainable and resilient practices.
	ISO 14224: Collection and Exchange of Reliability and Maintenance Data	Oil & Gas, Utilities	ISO 14224 provides a standard for collecting and exchanging reliability and maintenance data for equipment, especially in high-reliability industries.
Digital and IIoT-Driven Frameworks	**Reference Architecture Model for Industrie 4.0 (RAMI 4.0)**	Manufacturing, Industry 4.0	RAMI 4.0 is a reference architecture that connects industrial assets to Industry 4.0, emphasizing interoperability and asset lifecycle management.
	Industrial Internet Reference Architecture (IIRA)	IIoT, Industrial Automation	Industrial Internet Reference Architecture (IIRA) provides a framework for integrating physical assets into the digital ecosystem of the Industrial Internet of Things (IIoT).
	Asset Administration Shell (AAS)	Industry 4.0, Digital Twins	Asset Administration Shell (AAS) is the digital twin standard for Industry 4.0, facilitating interoperability and data exchange across systems.
	IEC 81346-1: Industrial Systems, Installations, and Equipment – Structuring Rules	Manufacturing, Energy, Utilities	IEC 81346-1 offers structuring principles and reference designations for industrial systems, helping organize and classify complex assets.
	IEC 62264/ISA-95: Enterprise-Control System Integration	Manufacturing	IEC 62264/ISA-95 bridges the gap between business planning and control systems, facilitating integration in manufacturing operations.
	OECD Framework for the Classification of AI Systems	OECD Countries	Emphasizes the importance of specificity in AI applications, the role of data types and quality, and the adaptability of AI models.
Governance and Data Management	**Control Objectives for Information and Related Technologies (COBIT)**	IT, Governance, Data Management	Control Objectives for Information and Related Technologies (COBIT) is a framework for IT governance and management, ensuring alignment with business goals.
	Industry Foundation Classes (IFC). ISO 16739-1:2024	Construction, Building Management	Industry Foundation Classes (IFC) is an open standard for data sharing in the construction and facility management industries, used in BIM.

Table 1. Overview of some key frameworks and standards supporting asset digitalization

2. THE NEED FOR DIGITALIZING ASSET MANAGEMENT

2.1. Why is crucial. Key Challenges.

In today's competitive and regulated environment, digitalizing maintenance management is essential. Failing to do so can lead to the following key challenges:

1. *Missed Opportunities with Modern Technologies:* Digital tools like IoT, AI, and predictive maintenance enable better decision-making, early fault detection, and automated workflows. Without these, companies face more downtime, inefficient repairs, and shorter asset lifespans.
2. *Falling Behind in Competitive Markets:* Digital maintenance improves operational efficiency, which is critical for staying competitive. Companies that don't adopt digital tools risk losing market share as competitors optimize their maintenance processes and reduce costs.
3. *Non-Compliance with Regulations:* As regulations require more detailed reporting, digitalization ensures compliance through automated data collection and reporting. Without it, companies face potential fines or operational restrictions due to non-compliance.
4. *Higher Operational Costs:* Traditional, reactive maintenance leads to unnecessary repairs and unplanned downtime. Digital tools allow for condition-based maintenance, reducing costs and optimizing resource use.
5. *Inability to Scale*: As organizations grow, manual or outdated systems struggle to keep up. Digital platforms scale seamlessly, supporting growing asset bases and complex operations. Without it, companies may become overwhelmed by operational complexity.
6. *Missed Sustainability Goals:* Digital maintenance supports sustainability by optimizing energy use, reducing waste, and extending asset life. Failing to digitalize means businesses miss out on sustainability benefits, risking regulatory and reputational issues.
7. *Reduced Agility in Responding to Disruptions:* Market disruptions demand quick responses. Digital tools enable real-time insights and remote operations, giving companies the agility to adapt. Without these, businesses face bottlenecks and slower reaction times.
8. *Decreased Asset Value and Shorter Lifecycles:* Without digital maintenance, assets deteriorate faster, leading to increased failure rates and shorter lifecycles. This drives up capital expenditure and reduces overall return on investment.

2.2. The benefit of digital processes

The benefits of digitalizing maintenance and asset management processes are numerous and transformative, providing organizations with tangible improvements in several areas:

- *Increased Efficiency:* One of the primary benefits of digital maintenance is the ability to improve the efficiency of maintenance activities. For example, automated diagnostics, smart scheduling, or remote monitoring reduce the time required to identify and address issues. This streamlining of processes leads to faster issue resolution and better resource management.
- *Cost Savings:* Digitalized maintenance can significantly reduce costs by optimizing maintenance schedules and minimizing unplanned downtime. Predictive maintenance models enable organizations to perform maintenance only when necessary, based on actual asset conditions, rather than following rigid, time-based schedules. This approach reduces unnecessary repairs and extends the lifespan of assets, ultimately lowering total maintenance costs.
- *Predictive Capabilities:* Predictive maintenance relies on real-time data from IoT sensors, AI algorithms, and machine learning models to predict when and where failures are likely to happen. This not only prevents costly breakdowns but also ensures that assets operate at optimal performance levels.
- *Improved Asset Reliability:* With digital tools in place, organizations can monitor the health and performance of assets continuously. Real-time data allows for more accurate decision-making, reducing the likelihood of unexpected failures and increasing overall system dependability.

- *Data-Driven Decision Making:* This approach allows maintenance teams to make more informed decisions, optimize maintenance activities, and align maintenance strategies with broader organizational goals.
- *Enhanced Sustainability:* Digital processes enable more sustainable maintenance practices by reducing waste, improving energy efficiency, and optimizing resource use. For example, by preventing unnecessary repairs and replacements, digital tools can help organizations reduce their carbon footprint and contribute to long-term environmental sustainability.

3. KEY CONSIDERATIONS FOR ASSET DIGITALIZATION

3.1. The Asset Digitalization Concept

This document recognizes the subtle differences between terms such as digitization, digitalization, and digital transformation (Raza et al., 2023). For the purposes of this work, "asset digitalization" is used as a comprehensive term that includes both the creation of asset data models and the transformative processes that generate new value (Gong and Ribiere, 2020). In line with this approach, the document focuses on three key dimensions:

- **Asset Digitization**: Refers to the creation of a foundational data and information model for an asset, effectively generating a digital twin with the necessary level of detail.
- **Asset Digitalization**: Expands beyond digitization to encompass the development of new processes, starting with the creation and ongoing updates of the digital twin. The emphasis is on enhancing the asset's value and management through emerging processes, which may not yet fully leverage digital technologies.
- **Digital Transformation**: The broader impact of this work contributes to digital transformation, aligning with the wider goals of enterprise transformation and the role of digitalization in shaping business and societal outcomes.

While digitalization solutions often originate from a technological perspective, it is essential according to the scope of this work to adopt a maintenance-focused approach to complement this. Such an approach ensures the longevity and reliability of digitalized assets, aligning with overall business objectives. This involves understanding and managing the digital capabilities of the IT solutions and overseeing the complete data and model management process, specifically tailored to maintenance needs, without delving deeply into the architecture design itself.

3.2. Background on Asset Data Models.

The question of how to digitalize an asset has been addressed by several key standards, one of which is ISO/IEC/IEEE 42010:2011, titled *"Systems and software engineering - Architecture description."* This standard broadly defines architecture as "the fundamental structure of a system, including the structure of its components, their relationships, and the principles and guidelines that govern their design and evolution over time" (ISO/IEC/IEEE 42010:2022 - Software, systems, and enterprise — Architecture description).

In systems engineering, architecture is essential because it provides a framework for describing the organization and interaction of system components, ensuring they work together to achieve defined objectives (Figure 1).

Another important standard is EN IEC 81346:2022, titled *"Industrial systems, installations, and equipment and industrial products - Structuring principles and reference designations - Part 1: Basic rules."* This standard offers principles for the classification and designation of objects within industrial systems, equipment, and plants. It plays a crucial role in organizing and structuring complex systems by offering a common language to identify system components based on their function, location, and product type (Figure 2).

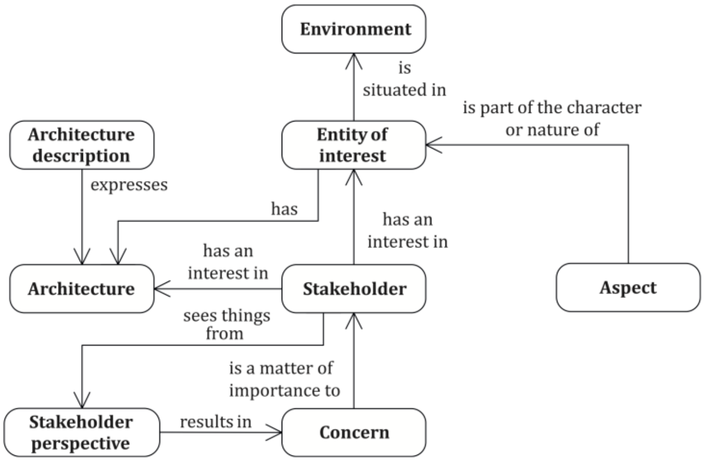


Figure 1. Relationships between concerns, aspects, and stakeholder perspectives as utilized in an architecture description according to ISO/IEC/41010:2022

In asset digitalization, EN IEC 81346:2022 systematically classifies and manages digital representations of assets, ensuring consistency and interoperability across different platforms and technologies such as IoT, digital twins, and asset management systems.

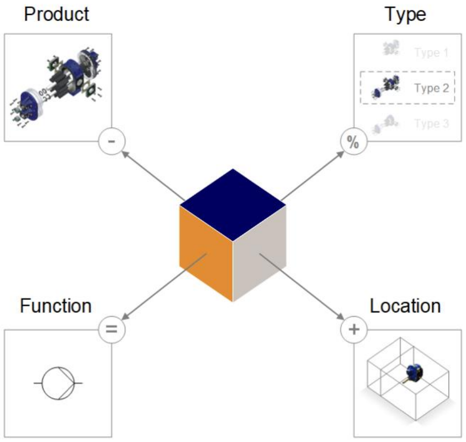


Figure 2. A technical view of the system of interest in relevant aspect EN IEC 81346.

In addition to these, ISO 14224:2016 provides valuable guidelines for the collection and exchange of reliability and maintenance data for equipment. This standard is crucial for digitalizing assets in industries where equipment reliability and maintenance are vital. It ensures that critical data on asset failure, performance, and maintenance history is consistently gathered and applied to improve operational efficiency.

ISO 14224:2016 complements asset digitalization by ensuring that all relevant operational and maintenance information is digitized and structured for better decision-making and performance analysis (Figure 3).

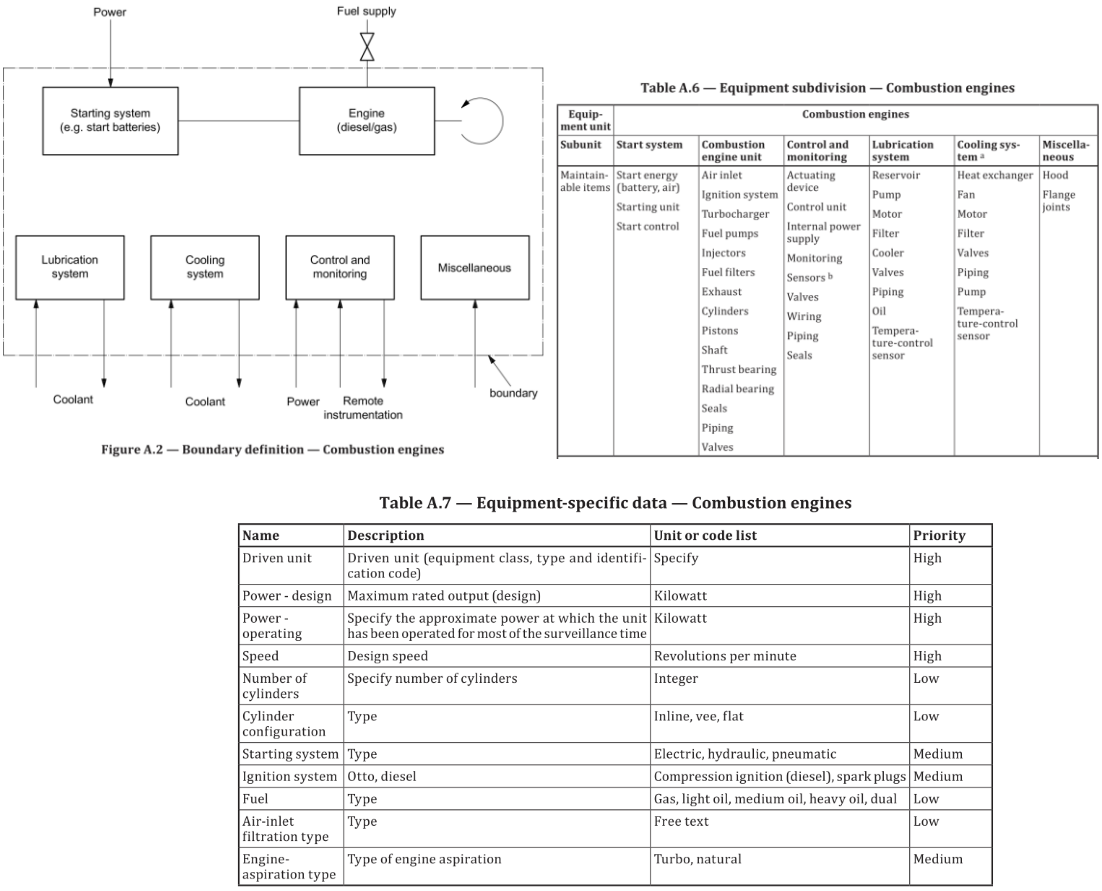


Figure A.2 — Boundary definition — Combustion engines

Table A.6 — Equipment subdivision — Combustion engines

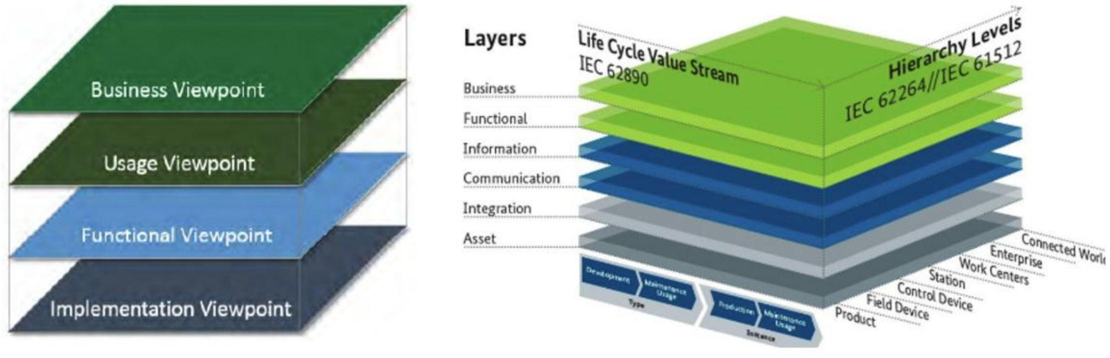
Equipment unit	Combustion engines					
Subunit	**Start system**	**Combustion engine unit**	**Control and monitoring**	**Lubrication system**	**Cooling system** [a]	**Miscellaneous**
Maintainable items	Start energy (battery, air) Starting unit Start control	Air inlet Ignition system Turbocharger Fuel pumps Injectors Fuel filters Exhaust Cylinders Pistons Shaft Thrust bearing Radial bearing Seals Piping Valves	Actuating device Control unit Internal power supply Monitoring Sensors [b] Valves Wiring Piping Seals	Reservoir Pump Motor Filter Cooler Valves Piping Oil Temperature-control sensor	Heat exchanger Fan Motor Filter Valves Piping Pump Temperature-control sensor	Hood Flange joints

Table A.7 — Equipment-specific data — Combustion engines

Name	Description	Unit or code list	Priority
Driven unit	Driven unit (equipment class, type and identification code)	Specify	High
Power - design	Maximum rated output (design)	Kilowatt	High
Power - operating	Specify the approximate power at which the unit has been operated for most of the surveillance time	Kilowatt	High
Speed	Design speed	Revolutions per minute	High
Number of cylinders	Specify number of cylinders	Integer	Low
Cylinder configuration	Type	Inline, vee, flat	Low
Starting system	Type	Electric, hydraulic, pneumatic	Medium
Ignition system	Otto, diesel	Compression ignition (diesel), spark plugs	Medium
Fuel	Type	Gas, light oil, medium oil, heavy oil, dual	Low
Air-inlet filtration type	Type	Free text	Low
Engine-aspiration type	Type of engine aspiration	Turbo, natural	Medium

Figure 3. Sample Equipment boundary definition, subdivision and specific data requirements for reliability & maintenance data exchange as in ISO 14224:2016,

Together, these standards—ISO/IEC/IEEE 42010:2011, EN IEC 81346:2022, and ISO 14224:2016—form a comprehensive framework for asset digitalization. They provide essential guidelines for structuring, classifying, and managing assets, ensuring that the complexities of digital assets are handled in a consistent and scalable manner. These standards are critical references for this study, enabling effective integration, interoperability, and long-term management of digitalized assets.



a) IIRA

b) RAMI 4.0

Figure 4. Layered reference architectures: a) IIRA; b) RAMI 4.0

In addition to the standards previously mentioned, two other critical frameworks that nowadays must be considered in asset digitalization are RAMI 4.0 (*Reference Architectural Model for Industrie 4.0*) and the IIRA (*Industrial Internet Reference Architecture*) presented in Figure 4. These frameworks provide essential guidelines for structuring and integrating digital assets within the broader context of Industry 4.0 and the Industrial Internet of Things (IIoT).

RAMI 4.0 introduces two axes—lifecycle and hierarchy in system integration— and introduces the *Asset Administration Shell* (AAS) as a notable contribution, playing a fundamental role in the digital transformation of the industry. The AAS serves as the "digital representation" or "digital twin" of a physical asset. In order to do so, defines several key data models that form the foundation of a Digital Twin. These models include the *Identification Model*, which provides unique identifiers for the asset; the *Structural Model*, organizing the asset's components and subcomponents; and the *Functional and Technical Data Model*, which captures performance specifications and technical attributes. The *Operational Data Model* includes real-time data from sensors, supporting monitoring and predictive maintenance, while the *Lifecycle Data Model* tracks the asset's entire lifecycle, including maintenance history and upgrades. Additionally, the *Behavioral and Simulation Data Model* simulates the asset's behavior in various conditions, and the *Asset Health and Status Model* monitors real-time asset health. The Security and Compliance Model ensures regulatory compliance and data integrity, and the Communication and Interaction Model governs how the asset interacts with other systems, ensuring interoperability in a digital ecosystem. These models collectively enable comprehensive asset management through the Digital Twin, supporting real-time monitoring, predictive analytics, and seamless system integration.

The *Industrial Internet Reference Architecture* (IIRA) is another key framework, designed specifically for the Industrial Internet of Things (IIoT). IIRA provides a reference architecture that enables the connection, management, and optimization of industrial assets within a digital ecosystem. It emphasizes scalability, interoperability, and security, ensuring that assets can be integrated into a larger, interconnected industrial network.

3.3. Dimensions to consider when digitalizing an asset.

The digitalization of assets is a multifaceted process that requires comprehensive frameworks to manage and optimize assets across their lifecycle. To fully harness the potential of digitalization, a structured approach is essential—one that incorporates different aspects of asset management. Drawing from established standards such as ISO/IEC/IEEE 42010:2011, EN IEC 81346:2022, ISO 14224:2016 and architectures like RAMI 4.0 and IIRA, we propose four key models that address the various dimensions of asset digitalization and management. These models not only align with existing systems engineering principles but also enhance the integration, monitoring, and decision-making capabilities of digitalized assets.

Based on this, a suitable recommendation would be to collect data to populate the following asset models:

1. *Asset Definition Model (ADM).* The *Asset Definition Model* provides a comprehensive framework for defining the structure, properties, and relationships of an asset within a digital system. This model aligns with the standards of ISO/IEC/IEEE 42010:2011, which emphasizes the need for a well-structured architecture description that defines the fundamental components and relationships of a system. The ADM is essential for creating a digital twin of the asset, ensuring that the digital representation is complete and can serve as the foundation for further processes, such as monitoring and maintenance. Additionally, the EN IEC 81346:2022 standard on object classification further supports this model by offering a systematic way to categorize and manage asset data within complex systems, ensuring consistency and interoperability across platforms.
2. *Asset Criticality Model (ACM)***.** The Asset Criticality Model addresses the prioritization of assets based on their impact on operations and their associated risks. This model is critical in ensuring that digitalization efforts focus on the most essential assets, maximizing value and minimizing downtime. RAMI 4.0, with its emphasis on asset lifecycle and hierarchical structures, supports this model by integrating the importance of criticality within the broader context of Industry 4.0. The ACM helps organizations focus on the assets that are most likely to influence operational efficiency and safety, ensuring that resources are allocated effectively in both short-term and long-term management.
3. *Asset Monitoring Model (AMM).* The Asset Monitoring Model facilitates real-time condition monitoring of assets using IoT networks and other digital technologies. This model draws from both RAMI 4.0 and IIRA, which emphasize the need for interconnected systems and continuous data flow between physical assets and digital systems. By integrating IoT sensors and signal processing, the AMM enables real-time visibility into asset conditions, supporting predictive

maintenance and minimizing unplanned downtime. This model also resonates with the Asset Administration Shell (AAS) in RAMI 4.0, which acts as the digital representation of the physical asset, ensuring seamless data exchange and analysis.

4. Intelligent Asset Management Models (IAMMs). The Intelligent Asset Management Models provide a higher-level view of asset health and performance, utilizing advanced analytics to deliver actionable insights. These models are closely tied to Asset Performance Management (APM) and Asset Investment Planning (AIP) systems and supports the goals of ISO 55000 on asset management, which emphasizes the need for integrating asset management practices into broader organizational goals. The IAMMs enable organizations to predict future asset conditions, optimize maintenance schedules, and align asset management with business objectives. Asset's health index model provides critical insights for long-term asset management planning, ensuring that digitalization efforts lead to sustainable value creation.

4. STRUCTURING DATA FOR DIGITAL ASSETS

In this document we recommend a structure of four data models for the digitalization of the asset:

4.1. The Asset Definition Model.

The *Asset Definition Model* serves as the foundational framework for describing and managing the comprehensive asset data that exists across various information systems and applications used for asset management. It leverages established standards like *IEC 81346-1:2022* and *ISO 14224:2016* to ensure that asset data is structured and represented consistently and effectively. These standards provide guidance on how assets are classified, organized, and maintained, promoting interoperability across platforms and systems.

The proposed Asset Definition Model includes four key dimensions that provide a holistic view of the asset. These dimensions ensure that the asset is properly registered, classified, located, and referenced in a way that supports digitalization and integration into management systems (Figure 5):

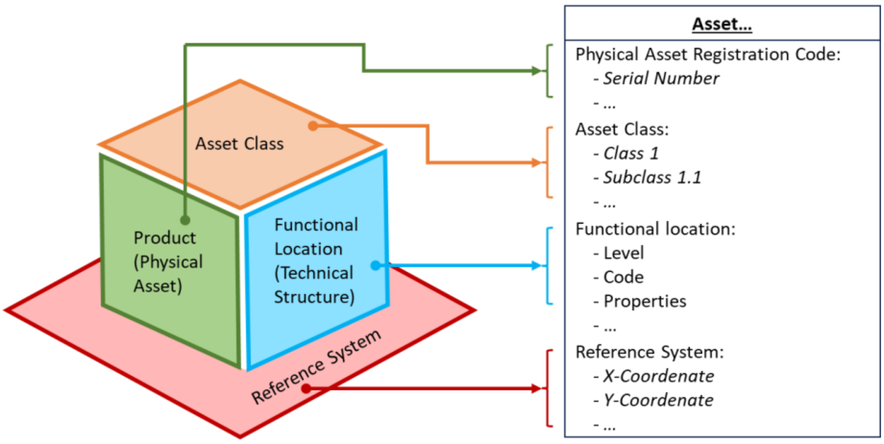


Figure 5: The Asset Definition Model

1. *The Physical Asset Registration Data.* The Physical Asset Registration refers to a code that can be the unique identifier assigned to a tangible object or entity within the asset management system. This code enables tracking and management of the asset throughout its lifecycle, from procurement and installation to operation and maintenance and consistent identification of assets across different platforms, ensuring accurate data exchange between systems. The physical registration code not only tracks the asset itself but also serves as the link between the physical and digital worlds, enabling the development of digital twins. These digital representations, which mirror the physical asset in real time, are essential for optimizing maintenance and management activities.

2. *The Asset Functional Location Data.* The Asset Functional Location refers to the physical or logical location where the asset is installed or used within the broader system or network. This concept is essential for assets that are part of larger systems, such as infrastructure networks, where their location plays a critical role in their operation and maintenance. For example, in a transportation system, the functional location of a bridge or tunnel must be precisely recorded to ensure it can be properly maintained and monitored. Additionally, functional location data supports the integration of Geographic Information Systems (GIS), enabling advanced spatial analysis and real-time monitoring of asset conditions.
3. *The Asset Class Data.* The Asset Class describes the technology and technical specifications of the asset, independent of its functional location. This classification system allows for the grouping of assets based on shared characteristics, such as their function, technology, or construction. Within IEC 81346, asset classes are further divided into subclasses (or types), which offer more granular categorization of assets within the same class. For example, a bridge may be classified under the "Infrastructure" asset class, with subclasses detailing specific types of bridges (e.g., suspension bridge, arch bridge). This classification is crucial for defining the asset's failure catalog or maintenance requirements. A structured asset class system allows organizations to manage large portfolios of assets better, ensuring consistency in the application of maintenance practices and technologies.
4. *Asset Reference System Data.* The Asset Reference System defines the coordinate system used to geolocate the asset within an infrastructure system or network. This is particularly important for assets that are spread over large geographical areas, such as power grids, transportation systems, or water networks. The choice of a reference system depends on factors like the location, precision requirements, and the specific needs of the infrastructure. By establishing a clear and consistent reference system, organizations can ensure that all stakeholders have access to accurate location data, which is critical for planning maintenance activities and responding to emergencies. The IEC 81346 standard supports the use of a reference system by providing guidelines for the classification and documentation of assets within spatial contexts. Integrating this system with IoT platforms further enhances the ability to track and monitor assets in real time

4.2. The Asset Criticality Model.

The *Asset Criticality Model* is an indispensable tool in maintenance and asset management, providing the foundation for risk-based decision-making and resource allocation. By prioritizing assets based on their criticality, organizations can focus their efforts on those assets that have the greatest impact on safety, performance, and operational continuity. Furthermore, by integrating with other asset management models—such as preventive maintenance, asset monitoring, and life cycle cost models—the ACM enables a holistic, data-driven approach to digitalization that supports long-term sustainability and resilience in infrastructure systems.

The primary function of the *Asset Criticality Model* is to rank assets according to their criticality. As suggested by Jinzhi et al. (2022), this analysis must allow the large-scale applicability of the model, its consistency with the organization's asset management strategy, and its ability to adapt to changes over time.

This ranking is crucial for decision-making, ensuring that the most critical assets receive the necessary attention and resources. Critical assets are those whose failure would have a significant impact on the system's overall performance, safety, or compliance with regulations. For instance, in the context of transportation infrastructure, the failure of a bridge could have severe consequences for public safety, traffic flow, and economic activity. The criticality ranking helps to identify where risks are highest, allowing organizations to prioritize maintenance activities, resource allocation, and monitoring efforts. This process not only reduces the likelihood of unexpected failures but also enhances the resilience and efficiency of the infrastructure system.

The *ACM* operates as a central component that connects to various other asset management models, facilitating an integrated approach to digitalization. These connections include preventive maintenance planning, real-time monitoring, and life cycle cost analysis, among others. A description of the importance of these model’s connections is the following:

- *Integration with Preventive Maintenance Models*: Once the criticality of assets is determined, the ACM integrates seamlessly with preventive maintenance models, such as Reliability-Centered Maintenance (RCM), Maintenance Task Analysis (MTA), and Risk-Based Maintenance (RCBM). These models define specific maintenance tasks, and their required frequency based on the criticality ranking of each asset. For example, highly critical assets may require more frequent inspections and preventive maintenance actions to mitigate the risk of failure and ensure continued operation. This integration is vital for aligning maintenance activities with the organization's asset management objectives. By connecting criticality analysis with preventive maintenance planning, organizations can develop maintenance strategies that focus on high-risk assets, reducing downtime and improving operational efficiency.
- *Connection with Asset Monitoring Models:* The Asset Monitoring Model plays a crucial role in managing critical assets by providing real-time insights into their condition and performance. By integrating with the ACM, asset monitoring becomes more focused on the most critical assets, enabling organizations to deploy IoT networks and advanced monitoring technologies where they are needed most. For instance, critical infrastructure assets, such as bridges, often lack continuous monitoring systems. However, by incorporating IoT sensors and signal processing capabilities, real-time monitoring of these assets becomes feasible. This real-time data feeds into predictive models, helping organizations detect early signs of deterioration or failure and take preventive action. The integration of monitoring models with the ACM is especially important for assets whose failure would have significant repercussions, such as public safety or operational disruption.
- *Connection with Life Cycle Cost Models:* The Asset Criticality Model also links to Life Cycle Cost (LCC) Models, which analyze the total cost of owning and operating an asset over its entire lifecycle. By understanding the criticality of each asset, organizations can make informed decisions about long-term investments and cost optimization. Criticality analysis helps in determining how much to invest in maintaining or upgrading an asset, based on its expected performance and the risk associated with its failure. For example, for highly critical assets, organizations might justify higher upfront costs in exchange for reduced long-term risk and lower maintenance costs. This connection between the ACM and LCC Models ensures that decisions about asset replacement, refurbishment, or disposal are made in a way that balances risk, performance, and cost over the asset’s lifespan.
- *Adaptability to Organizational and Environmental Changes:* As infrastructure systems evolve, asset criticality may shift due to changes in technology, environmental conditions, or operational priorities. The ACM must be flexible enough to adapt to these changes, allowing organizations to re-evaluate asset priorities over time. For instance, as climate change continues to impact the performance of infrastructure assets, the criticality of certain assets may increase, necessitating a more proactive approach to their management.

4.3. The Asset Monitoring Model.

The *Asset Monitoring Model* is a critical part of asset digitalization, providing the necessary infrastructure for real-time monitoring and decision-making. By utilizing IoT networks and cloud computing, organizations can gain continuous insights into asset conditions, enabling predictive maintenance and optimizing asset performance. When integrated with other asset digitization models, the monitoring model supports a comprehensive and proactive approach to asset management, ensuring long-term sustainability and operational efficiency.

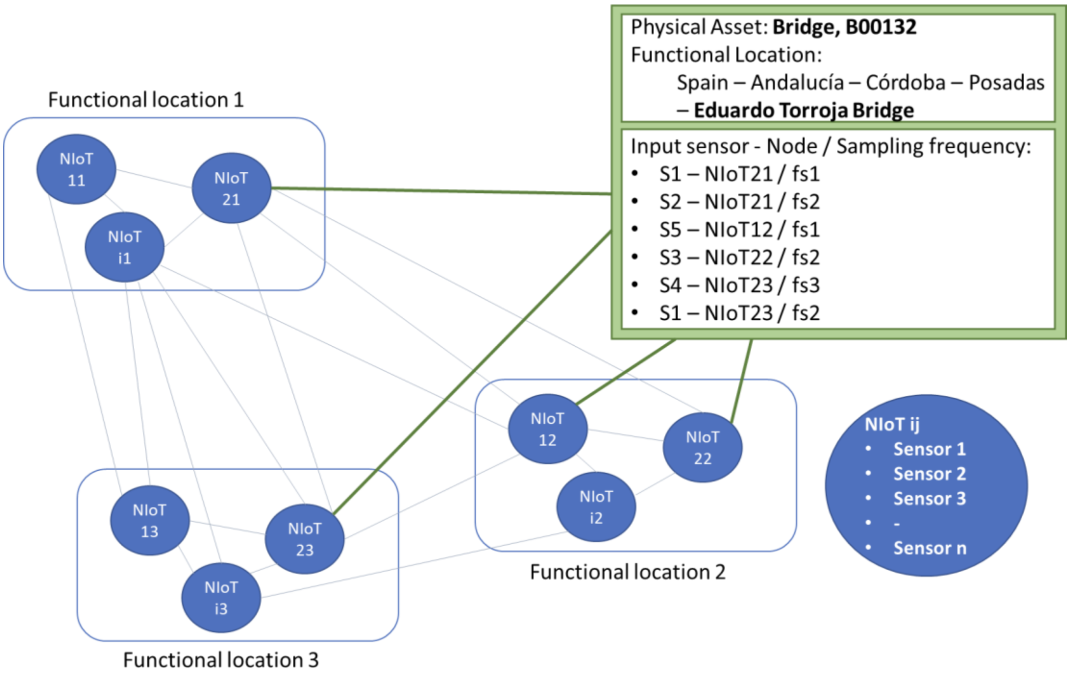


Figure 6. The Asset Monitoring Model

The asset monitoring process begins with the development of a comprehensive monitoring solution tailored to each specific asset. This involves signal integration, which is the process of collecting, converting, and interpreting signals from sensors placed on or around the asset (Figure 6). The collected data is then processed using an Extract, Transform, Load (ETL) system, where the signals are transformed into meaningful, actionable information related to the asset's health and performance.

Elements to identify in this asset monitoring model are the following:

- *IoT Networks and Signal Processing:* At the core of the Asset Monitoring Model is the use of IoT networks. An IoT network consists of three main components: sensors, nodes, and cloud computing systems. Sensors are deployed on the asset to measure various physical parameters such as temperature, vibration, strain, or pressure. These sensors collect real-time data that is crucial for monitoring the asset's condition.

Nodes play a critical role in the system by aggregating data from multiple sensors. Each node acts as a central point for a group of sensors, ensuring efficient communication and data transfer. These nodes are responsible for local data processing and transmitting the information to the cloud. Cloud computing platforms then store, analyze, and present the data, offering end-users a detailed and comprehensive view of the asset's status.

- *Design of the Asset Monitoring System.* The design of an asset monitoring system typically follows an IoT-based framework, which includes the following key layers:
    - Acquisition and Local Processing: Data is acquired from sensors located on the asset, and local processing is performed at the sensor nodes. This allows for the immediate interpretation of data before it is transmitted, enabling faster response times.
    - Information Transport Network: The data collected by sensor nodes is transmitted through a secure communication network, typically via wireless protocols. This network ensures that data flows seamlessly from the sensors to the cloud.
    - Processing Server: At the heart of the system is the processing server, which hosts essential services for data transformation, analysis, and presentation. This server is responsible for executing the ETL process and ensuring that the data is structured and analyzed in alignment with asset-specific digitization models.

To ensure scalability, the system can adopt a microservices-based architecture. This approach allows the system to handle large-scale data from multiple assets, ensuring that each component—whether it is data gathering, storage, or analysis—can be managed independently and scaled as needed.

- *Integration with other Asset Digitalization Models.* The Asset Monitoring Model is not a standalone process. It works in conjunction with other asset management models, such as the Asset Definition Model and the Intelligent Asset Management Model. By integrating real-time data with asset-specific models, organizations can gain a comprehensive view of asset performance, health, and criticality. For example, in infrastructure management, such as monitoring a bridge, real-time data from sensors strategically placed on the structure can be used to detect stress, wear, and potential points of failure. This data can then be fed into an intelligent asset management system to predict when maintenance should be scheduled and what specific actions are required to prolong the asset's life.
- *Hardware and Software Integration.* The Asset Monitoring Model relies on the integration of both hardware and software components. Hardware includes the physical sensors and nodes installed on the asset, while software involves the local and cloud-based systems that process and analyze the data. The system requires:
  - Real-time Operating Systems (RTOS) to manage sensor data and ensure timely responses to changing asset conditions.
  - Wireless communication protocols to transmit data from sensors to nodes and from nodes to the cloud.
  - Data storage and data processing solutions, capable of handling large volumes of information, typically housed on cloud platforms.
- *Server and Centralized Processing.* At the heart of the monitoring system is the server responsible for centralized data processing and management. This server collects information from the various nodes and executes tasks such as data storage, real-time data processing, and presenting insights to end-users through dashboards or other visualization tools. As assets and their monitoring systems grow in complexity, the server's architecture must be scalable and capable of handling increasingly large datasets, which is why a microservices-based development is commonly adopted. This approach allows for individual tasks, such as data collection or processing, to be scaled independently based on demand.

4.4. The Asset Intelligent Maintenance Model.

The Intelligent Asset Management Models (IAMM) represents the final layer in asset digitalization, focusing on integrating real-time and historical asset data for advanced decision-making processes. Once an asset's data has been captured, processed, and structured (via the Asset Definition and Monitoring Models), and its criticality is addressed (via the Asset Criticality Model), the need arises to connect this data with human reasoning and decision-making tools.

Intelligent asset management relies heavily on the development and integration of robust data models that allow for the digital execution of key methodologies, such as RCFA, RCM, CBM), RAMS, LCC, AHI, etc. These data models provide the essential framework to capture, organize, and analyze the wealth of information generated by industrial assets, supporting decision-making processes that drive asset optimization.

By structuring asset data into models for identification, criticality, monitoring, and intelligent management, it becomes possible to effectively apply advanced maintenance techniques in a digital context.

The integration of these data models ensures that decision-making processes are streamlined, and that predictive analytics and simulation tools are leveraged to generate actionable insights. This approach enables organizations to move beyond manual methods, optimizing maintenance strategies and aligning them with broader business goals through data-driven insights.

5. DIGITALIZATION OF MAINTENANCE AND ASSET MANAGEMENT PROCESSES

5.1. Key managerial areas digitally supported.

Most of the data that is collected through new digital technologies can be used to increase the effectiveness of asset management decision-making. Consequently, the types of asset management decisions and their importance in meeting the organization's AM objectives need to be identified. The importance of each reporting requirement associated to a given decision-making process can be estimated by identifying the benefits of better a reporting and decision making and the risks associated with poor (non-data-driven) decision making or reporting. To this end, the process to follow could be (Dunn, 2019):

1. Identify the requirements of all key stakeholders with respect to the provision of information.
2. Identify the most critical assets and then select the information that must be considered that will lead to effective decision making. Finally, it is necessary to determine what data is needed to obtain this information. The necessary data could take many different forms, including:
    - Data about the assets (themselves, current condition, current level of performance).
    - Data relating to the activities that have been performed on the assets (operational activities, maintenance activities and modifications, upgrades or replacements);
    - Data about the financial or other impacts if the assets underperform or fail to perform at all.
    - Data relating to safety, environmental or other incidents.
    - Data relating to expected future asset performance, costs, and risks.
    - Etc.
3. Identifying the types of decisions which will have the greatest potential impact on the achievement of asset management (and organizational) objectives. The decisions can be made at many different organizational levels, including:
    - *Strategic Decisions* – potentially those with the greatest potential business impact, capital investment and allocation of operating expenditure decisions. Also, those decisions for which objective data is most likely to be difficult to obtain and analyze.
    - *Management Decisions* – such as to replace or upgrade an asset to meet specific business needs, about the timing of these major events, also those related to the allocation of working capital (such as for spare parts holdings), decisions relating to whether to insource or outsource activities.
    - *Operational Decisions* – involved with short term control of maintenance and operational activities, these are technical decisions relating to day-to-day Operations.

Some experts agree that there has been unequal attention paid to the *management* and *operational* areas over the last decades where many business resources were spent on activities to get the jobs done more efficiently (Crespo Márquez, 22). For instance, master asset registers were created, work management systems and procurement systems were developed, and communication with craftsmen was improved. However, it seems that a better balanced and more *strategic* view is needed, understanding business priorities in work and investments.

5.2. Starting from the Maintenance Management Processes and Framework

Effective maintenance management requires a structured approach—a systematic process that organizes management activities into a series of "management building blocks". These blocks serve as key areas of focus, and a "framework" is then established, grouping the techniques and methods used to support decision-making in each of these areas. A generic maintenance management model for both built and in-use assets, consisting of eight sequential management building blocks is presented by Crespo (2007), as illustrated in Figure 8.

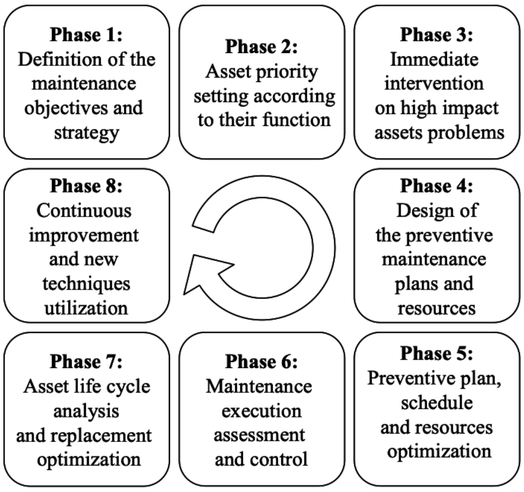


Figure 8. Maintenance Management Model

Each of these building blocks represents a critical decision-making area for asset maintenance and lifecycle management. Techniques, methods, and models within each decision area are used to guide and streamline decision-making, some of which are shown in Figure 9.

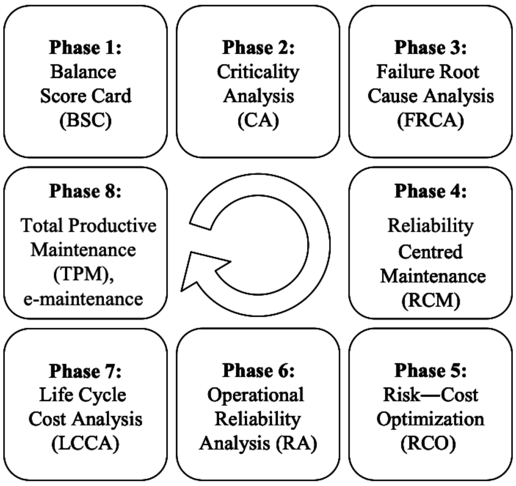


Figure 9. Sample methods and models (Crespo Márquez A, 2007)

5.3. The DMM Processes & Framework

In digital maintenance management (DMM) data plays a central role, enabling asset managers to access diverse information that can significantly improve decision-making.

DMM is possible thanks to the inclusion of new data-related processes and a digital framework. The framework provides a comprehensive approach to managing and optimizing maintenance activities in the processes by leveraging advanced digital tools and data-driven decision-making. This framework integrates multiple models, each serving a critical function in the digitalization of maintenance processes.

To have a better visualization of the overall DMM process we can use an *Input—Process—Output* diagram, as shown in Figure 10 (taken from Crespo Márquez A, 2022).

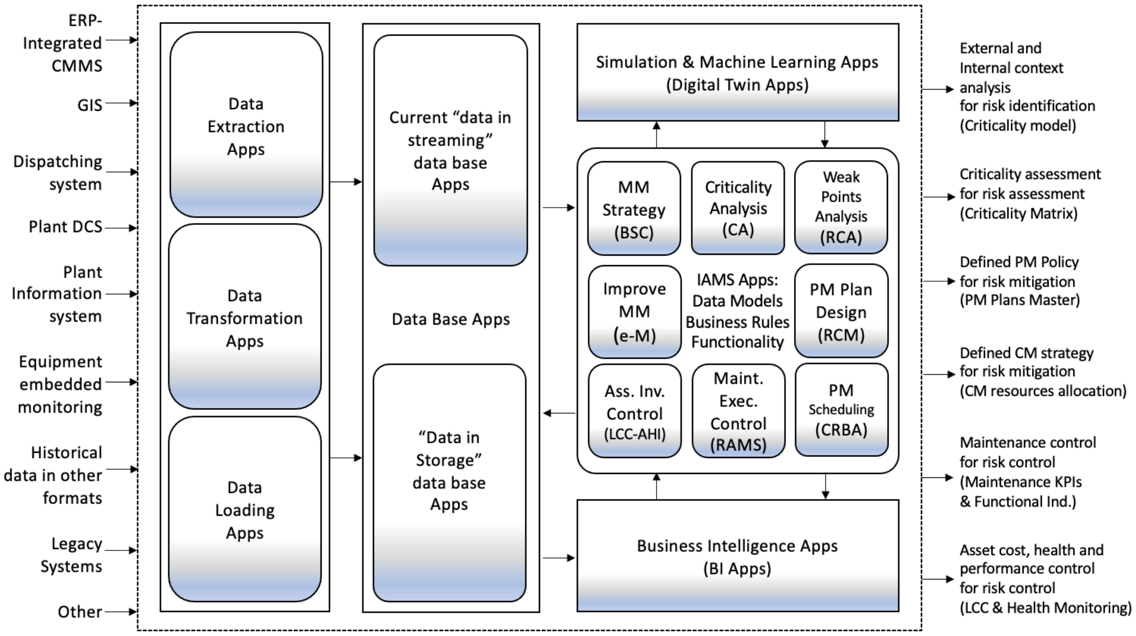


Figure 10. Input—Process—Output Diagram of the DMM Framework

The difference with previous section maintenance management processes can be explained as follows: Although the core processes of MM remain the same (in figure 10 now named as IAMS Apps), four new data related processes are incorporated to:

1. Extrac, transform, and load data from various sources into structured, accessible formats, to flow into decision-making systems. Process accomplished by the ETL Apps in Figure 10.
2. Organize and maintain the amounts of data collected, to serve as the foundation for decision-making in each management area IAMS Apps, whether for strategic planning, operational control, predictive maintenance or whatever. Process accomplished by the Data Base Apps in Figure 10.
3. Generate Digital Twin models to serve as a virtual replica of the physical assets, integrating real-time operational data, historical performance, and predictive analytics. To simulate asset behavior under various conditions and scenarios, enabling to account on these results for proactive decision-making. Process accomplished by the DT Apps in Figure 10.
4. Provide the interface to extract actionable insights from the data repositories. According to specific business needs, to align with organizational goals. Process accomplished by the BI Apps in Figure 10.

Let's now explain a bit the new supporting structure, the framework of the comprehensive DMM. It can be presented as consisting in different models: ETL, Database, IAM, AI, and BI models:

1. *ETL Model (Extract, Transform, Load):* The ETL process is the backbone of digital maintenance management, facilitating the extraction, transformation, and loading of data from various sources into structured, accessible formats. The ETL model automates this process, allowing real-time and historical data to flow efficiently into decision-making systems. This includes:

- *Historical data* on asset management, planning, and costs, providing insights into past maintenance activities and expenditures.
- *Geographic and operational data* on assets, which considers environmental conditions and location changes, critical for understanding asset behavior under different contexts.
- *Real-time equipment status*, including alarms, degradation patterns, and thresholds, to monitor current conditions and anticipate potential failures.
- *Predictive data*, derived from reliability studies and AI-based models, forecasting future maintenance needs based on trends and degradation rates.
- *Etc.*

The ETL model ensures that data is transformed to meet specific information and format requirements before being loaded into cloud-based databases using Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) tools, making it readily accessible for further analysis. ETL can be designed and supported by big-data tools having these capabilities.

2. *Database Management Model (DB).* The Database Management Model is responsible for organizing and maintaining the vast amounts of data that are collected, transformed, and stored. In this model, the cloud databases allow for scalable storage, enabling organizations to store and retrieve large volumes of data in real time. Data can be queried and retrieved on-demand, and with advanced data structuring, it becomes easy to integrate with other digital tools within the framework. This model ensures that relevant data is always accessible, secure, and properly organized, allowing for seamless integration into decision-making processes.

3. *Intelligent Asset Management System (IAMS) Models.* The Intelligent Asset Management System (IAMS) models are the core part, are possible thanks to the proper digital definition of the asset and sustain decision-making. These models analyze and organize data from different repositories to support specific maintenance and asset management decisions. IAMS models may include:
   - *RCM* Models. To design maintenance of very crucial systems.
   - *Predictive maintenance* models that use real-time and historical data to forecast equipment failure and optimize maintenance schedules.
   - *Risk and reliability* models that assess the likelihood of failure based on various factors such as operational stresses, maintenance history, and environmental conditions.
   - *Asset health indexing*, which evaluates the condition of each asset in relation to its operational parameters and environment, helping to prioritize maintenance activities.
   - *Life cycle costing* models. To determine the cost of ownership and better reinvestments decisions.

   IAMS apps work alongside ETL tools to create custom data repositories tailored to each decision-making block. They ensure the selection of the right data for each decision, applying appropriate business rules for optimal asset management. Additionally, IAMS apps interact with DT Apps (machine learning and simulation models) to generate additional data providing further analytical capabilities.

4. *Machine learning and Simulation Models (DT).* To generate the Digital Twin models to serve as a virtual replica of the physical assets, integrating real-time operational data, historical performance, and predictive analytics. This allows maintenance teams to simulate asset behavior under various conditions and scenarios, enabling proactive decision-making. The Digital Twin is not just a static representation but a dynamic, evolving model that continuously updates with live data from sensors and IoT networks. It enables:
   - Simulations of how assets will perform under different stress conditions, allowing organizations to test maintenance strategies before implementing them.
   - Predictive analytics, providing forecasts of equipment failure, performance degradation, and operational inefficiencies.
   - Real-time monitoring, which ensures that maintenance teams are alerted to any deviations in asset performance, enabling swift corrective action.

   These models are vital for developing deeper insights into asset behavior, supporting both immediate operational decisions and long-term planning.

5. *Business Intelligence (BI) Models for User Interaction.* The Business Intelligence (BI) models provide the critical interface between the data and the end users, making it easy to extract actionable insights from the data repositories. BI models are tailored to specific business needs, allowing maintenance managers to generate reports, dashboards, and analytics that align with organizational goals. The BI apps within the DMM framework enable:
   - Real-time reporting on asset performance, maintenance schedules, and operational efficiency.
   - Interactive dashboards that allow users to explore data through customizable visualizations, facilitating decision-making at all levels.
   - Advanced analytics, helping users interpret data trends, forecast future performance, and assess the impact of maintenance interventions.

   BI models also support collaboration by enabling multiple stakeholders to access the same data and insights, ensuring that maintenance decisions are aligned with broader business objectives.

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